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Research-Cottrell, Inc, Bound Brook, NJ

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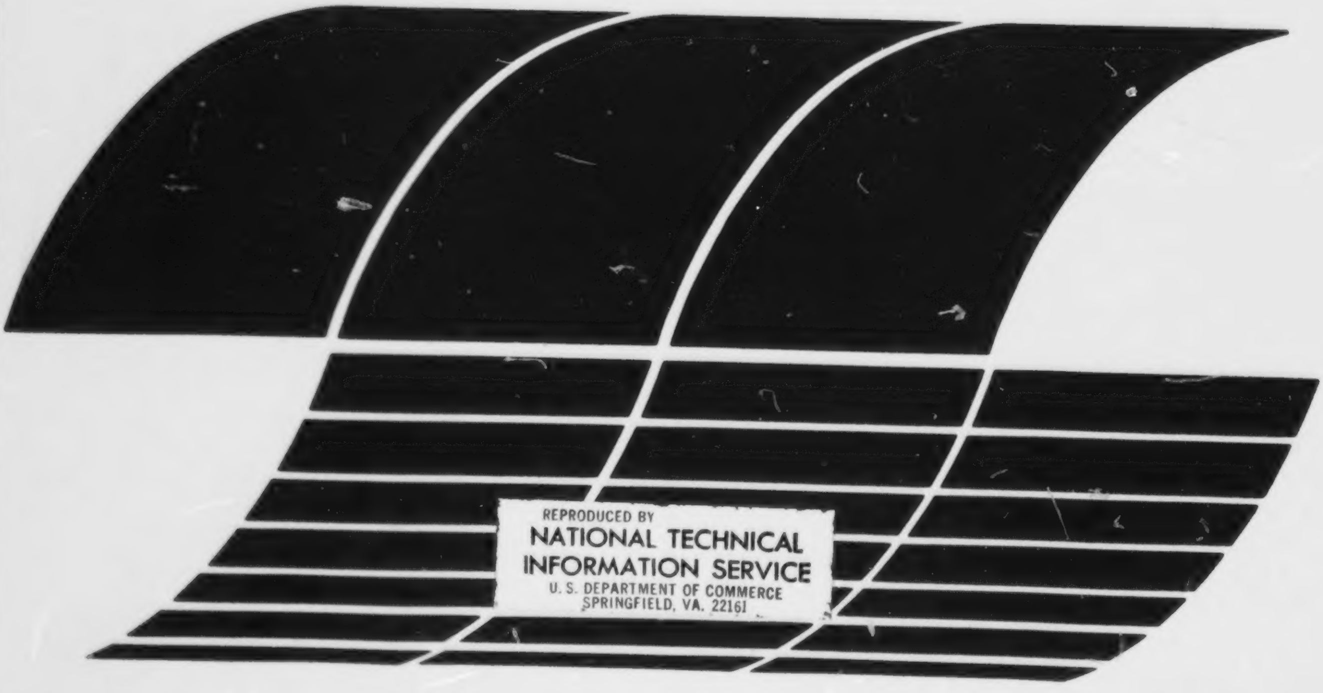

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16. ABSTRACT The report gives results of an 18-month evaluation of the R-C/Bahco combined flue gas desulfurization and particulate removal system on a stoker-fired industrial boiler at Rickenbacker AFB, Ohio. Particulate emissions were reduced to as low as 0.15 lb/million Btu. SO2 emissions were reduced to as low as 0.1 lb/million Btu with lime and 0.2 lb/million Btu with limestone while burning 2-4% sulfur midwestern coal at firing rates from 20 to 200 million Btu/hr. Operating costs, including maintenance, were $5.28 per ton of coal burned for lime and $4.27 per ton for limestone, exclusive of capital costs. There were no problems with scale formation or plugging with either reagent. The system met all emission and operating cost guarantees.

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Flue Gases	Stokers	Stationary Sources	21B	
Desulfurization	Coal	Bahco Process	07A,07D	21D
Sulfur Oxides	Scrubbers	Particulate	07B	
Dust Control	Limestone			08G
Boilers	Calcium Oxides		13A	

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by

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CES 272 ABSTRACT

A comprehensive test program which characterized the particulate removal, sulfur dioxide removal, operating costs, maintenance costs, waste product properties operating experience and capacity of a size 50 R-C/Bahco scrubbing system installed to treat flue gas from coal fired boilers at Rickenbacker AFB, Columbus, Ohio, was completed. Tests were conducted over an 18 month period during which 27,216 tons of coal were burned.

The results from this program demonstrate that this system is capable of controlling both particulate and sulfur dioxide emissions from the combustion of high sulfur (2-4%) mid-Western coal at firing rates from 20 MM to 200 MM Btu/hr.

Particulate emissions were reduced to as low as 0.15 lbs./MM Btu. Sulfur dioxide emissions were reduced to as low as 0.1 lbs./MM Btu with lime and 0.6 lbs./MM Btu with limestone. Operating costs were $5.28 per ton of coal burned including $0.21 maintenance costs when using lime. A cost of $4.27 per ton for optimum operation with limestone was projected. Waste product properties relative to dewatering handling and disposal were found to be similar to those measured for other FGD waste products.

Operation of the system required less than 2,000 man hours per year. During the test program, the system experienced downtime due to auxiliary equipment defects, an inadequate spare parts inventory and minor system modifications. There was no process related downtime. Based on the observations made during the test programs, future system availability above 95% is projected.

CONTENTS

Page

Abstract 2
List of Figures 5
List of Tables 7
List of Abbreviations and Symbols 9
Executive Summary 11

1. Introduction 19
2. R-C/Bahco Scrubbing System 22
    Process Description 23
    Major Equipment 23
3. Test Program 33
    Test Description 33
    Process Variable Test Design 36
4. Operability/Material Balance Test Results 43
    R-C Bahco Scrubber Operating Limits 43
    Material Balance 46
5. Sulfur Dioxide Removal Tests 56
    Preliminary SO_2 Removal Tests 56
    Lime Screening Tests 56
    Lime Verification Tests 64
    Limestone Process Variable Tests 68
    Lime vs. Limestone 73
    Conclusions 76
6. Particulate Removal Tests 77
    Initial Particulate Tests 77
    Fractional Efficiency Tests 81
    Particulate Performance Models 86
    Conclusions 100
7. Scrubber Sludge Characterization Tests 101
    Slurry Dewatering 102
    Transportability 112
    Physical/Structural Properties 113
    Environmental Acceptability 114
    Conclusions 116
8. Operating Experience 117
    Monthly Operating Summaries 121
    Evaluation of Downtime 121
    Scrubber Inspections 127
    Conclusions 133

CONTENTS (CONT.)

Page

9. Operating and Maintenance Costs. 136
   - Operating Costs 136
   - Maintenance Costs. 139
   - Recommended Operating Conditions . . . 141

Appendices. 143

A. Conversion Factors: British to SI Units . . 143
B. Analytical and Testing Methods 145
C. Material Balance Test Data 153
D. Lime Test Data 162
E. Reagent and Coal Data. 173
F. Lime Verification Test Data. 177
G. Limestone Test Data. 185
H. Particulate Test Data Summary. 195
J. R-C/Bahco Scrubber Operating Log 211
K. Sulfur Dioxide Performance Test Results. . . 215

LIST OF FIGURES

Number Page

1-1 The R-C/Bahco Scrubber at RAFB 20

2-1 The R-C/Bahco System Process Flow Diagram. 24

2-2 Lined Storage Pond at RAFB 28

3-1 The Characterization Program Test Schedule 34

4-1 Verification of Inlet and Outlet SO_2 Concentration Data 50

4-2 The Relationship between Slurry Solids Concentration and Specific Gravity 51

4-3 A Comparison of Gas Flow Rate Derived from Fan Performance Data and Pitot Tube Measurements . . . 55

5-1 The Relationships between SO_2 Emission Rates and Lime Stoichiometry 58

5-2 SO_2 Removal Efficiency as a Function of Lime Stoichiometry 66

5-3 SO_2 Verification Test Results 67

5-4 SO_2 Removal Efficiency as a Function of Limestone/SO_2 Stoichiometry and Slurry Pumping Rate. 70

5-5 Comparison of Predicted and Observed SO_2 Removal Efficiency for Limestone 71

5-6 The Effect of Lime and Limestone Stoichiometry on Dissolver pH 75

6-1 The Effect of Scrubber Pressure Drop on Particulate Emission Rates 79

6-2 A Comparison of Various Particle Size Distributions for RAFB 80

LIST OF FIGURES (CONT)

Number Page

6-3 The Effect of Total Scrubber Pressure Drop on the Cut Off Diameter for 90% Collection Efficiency . . . 83

6-4 The Effect of Total Scrubber Pressure Drop and Gas Rate on the Cut Off Diameter for 50% Collection Efficiency 84

6-5 Particulate Collection Efficiency as Related to Particle Size at RAFB. 87

6-6 Examples of Reentrainment from the R-C/Bahco Scrubber at RAFB. 88

6-7 An Example of Bypassing from the R-C/Bahco Scrubber at RAFB. 90

6-8 The Effect of Venturi Pressure Drop on Liquid Pickup . 92

6-9 A Comparison of Observed and Predicted Particulate Penetration 97

6-10 A Comparison of Observed and Predicted Particulate Collection Efficiencies for the R-C/Bahco Scrubber at RAFB. 98

7-1 A Comparison of Lime and Limestone Slurry Settling Rates. 103

7-2 The Effect of Operating Time and Slurry Feed Concentration on Centrifuge Cake Density 105

7-3 Filtration Rate as a Function of Form Time and Slurry Concentration 108

7-4 A Photomicrograph of Lime Sludge Showing Calcium Sulfite Crystals 110

7-5 A Photomicrograph of Limestone Sludge Showing Gypsum Crystals 111

8-1 A Summary of the Operation of the R-C/Bahco Scrubber at RAFB from March 1976 to May 1977. 118

8-2 Bahco Scrubber Module. 128

8-3 R-C/Bahco Scrubber Internals Showing the Venturi, Pan and Spray Manifold in the Second Stage 130

8-4 Build up on the Vanes in the Stack Area After Six Months of Operation. 135

LIST OF TABLES

Number		Page
2.1	Typical System Operating Conditions	12
3.1	Screening Test Matrix for the R-C/Bahco Test Program.	38
3.2	Target Levels for Lime Tests.	39
3.3	Target Levels for Limestone Tests	40
3.4	Analytical Tests.	42
4.1	R-C/Bahco Scrubber Operating Limits	44
4.2	Material Balance Results	48
4.3	Slurry Solids Concentration and Specific Gravity	52
4.4	Comparison of Gas Flow Measurement Techniques	54
5.1	SO_2 Removal Efficiency Data	57
5.2	Lime Screening Test Variable Levels	59
5.3	SO_2 Variable Screening Test Results	61
5.4	Lime Screening Test Data Summary.	62
5.5	Lime Verification Test Results.	65
5.6	Limestone Screening Test Data Summary	69
5.7	Lime and Limestone Slurry Analyses.	74
6.1	Particulate Emission Rates.	78
6.2	Inlet Particle Size Distributions	78
6.3	Fractional Efficiency Test Results.	82

LIST OF TABLES (CONT)

Number Page

6.4 Venturi Liquid Pickup Rate 91

6.5 Penetration Model Coefficients 96

6.6 A Comparison of One and Two Stage Models 99

7.1 Settling Test Results. 104

7.2 Centrifuge Test Results. 106

7.3 Filter Leaf Test Results 109

7.4 Slurry Solids Composition. 109

7.5 Transportability Test Results. 113

7.6 CBR Test Summary 114

7.7 Sludge Leachate Analyses 115

8.1 Down Time Related to Auxiliary Equipment 119

8.2 Down Time From Other Sources 120

9.1 Operating Cost Summary 136

9.2 Equipment Power Requirements 137

9.3 Optimum Operating Costs. 139

9.4 Maintenance Labor and Material Costs 140

9.5 Summary of Recommended Operating Conditions. 142

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

CBR	California bearing ratio
COD	chemical oxygen demand
gr	grains
in. W.C.	inches water column
lb-m	pound moles
LOI	loss on ignition
mg	milligrams
MM	million
ppb	parts per billion
ppm	parts per million
SCFD	standard cubic foot, dry
SCFMD/ SCFMW	standard cubic feet per minute, dry/wet
S.G.	specific gravity
St.	stoichiometry
TDS	total dissolved solids

SYMBOLS

a_1, a_2	coefficients for $(L/G)_1$, $(L/G)_2$
C'	Cunningham correction factor
Cin	inlet particle concentration between 1st and 2nd stages
C_{2out}	particle concentration leaving 2nd stage
D	collector droplet size
d_p, D_p	particle diameter
$D_{P_{50}}$	diameter at which scrubber removes 50% of particulate
$D_{P_{90}}$	diameter at which scrubber removes 90% of particulate
F_c	initial feed concentration (% solids)
G	gas flow rate
H_c	height of liquid in cylinder
H_o	initial height of sludge layer

SYMBOLS (Cont.)

H_u	underflow sludge layer height
L	slurry flow rate
L_1, L_2	first, second stage slurry flow rates
L/G	liquid/gas ratio
P_{o_A}	total penetration
P_1, P_2	penetration through 1st, 2nd stages
PPMf	flocculant concentration, ppm
SG_L	liquid specific gravity
SG_m	mixture specific gravity
SG_s	solids specific gravity
SG_f	feed specific gravity
SG_u	underflow sludge specific gravity
t	settling time for solids with concentration UF_c
T_{av}	average gas temperature
UF_c	underflow sludge concentration
V_{ga}	average gas velocity
V_o	undisturbed upstream velocity
$\bar{X}$	mean concentration
$\Delta P_1, \Delta P_2$	first, second stage pressure drops
η_{OA}	overall efficiency
μ	microns
μ'	gas viscosity
ρ_g	gas density
ρ_p	particle density
σ	standard deviation
Ψ	inertial impaction parameter

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The cooperation of the base civil engineering staff of Rickenbacker AFB, Colonel Earl L. Krueger, Base Civil Engineer, James B. Rasor, Associate Base Civil Engineer, and Herbert Robinson, Scrubber Technician, is gratefully acknowledged.

The U. S. Air Force made the R-C/Bahco flue gas desulfurization system at RAFB available for this test program and contributed in every possible way to the success of the program.

EXECUTIVE SUMMARY

INTRODUCTION

This report describes the results of a program sponsored by the Environmental Protection Agency and performed by Research-Cottrell (R-C) under a contract with the United States Air Force (USAF) at the R-C/Bahco sulfur dioxide and particulate scrubbing system installed at Rickenbacker Air Force Base (RAFB) in Columbus, Ohio. The program was conducted to characterize the performance of an R-C/Bahco scrubber handling flue gas from the combustion of midwestern high sulfur coal.

The R-C/Bahco system was designed, erected and installed by R-C under a contract funded by the USAF as part of their program to demonstrate the viability of air pollution control technology. The system installed at RAFB in the first application of this technology in the U.S. and its first application anywhere on a coal fired boiler. The results of the R-C/Bahco characterization program are presented in this report.

The scrubbing facility at RAFB, which consists of a size 50 R-C/Bahco scrubber and auxiliary equipment, was designed to treat 108,000 ACFM[1] of flue gas at 475° F containing 1500 to 2000 ppm of sulfur dioxide and 0.2 to 2.0 grains per SCF of particulates.

The R-C/Bahco system is a two stage venturi scrubber manufactured by Research-Cottrell under license from A. B. Bahco of Sweden. The reagent storage and feed system was designed to handle both lime and limestone. The system was designed to handle up to 108,000 ACFM of flue gas at 475°F, which is equilavent to a coal firing rate of 200,000,000 Btu/hr, as well as summer load conditions when the coal firing rate is under 20,000,000 Btu/hr. The system was guaranteed to meet Ohio emissions standards in force in 1974. These standards required an SO_2 removal of 83% at maximum load for 3.5% sulfur coal, i.e. a maximum emission of 1.0 lbs. of SO_2 per million Btu of coal fired. The standards also limited particulate emissions to 0.16 lbs. per million Btu at maximum load.

Maximum requirements for power (600 KW average), water (45 gpm), lime (2010 tons per year a 1.1 lime-SO_2 stoichiometry), and operating labor (2 man hours per shift plus supervison) were guaranteed by R-C.

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(1) Although it is the policy of the EPA to use the S.I. system for quantitative descriptions, the British System is used in this report. Readers who are more accustomed to S.I. units are referred to the conversion table in Appendix A.

Typical scrubber operating conditions are listed in Table 2.1.

TABLE 2.1 TYPICAL SCRUBBER OPERATING CONDITIONS

Flue Gas	64,000 ACFM @380°F
SO_2 Concentration	1390 ppm
1st Stage ΔP	10. in. W.C.
2nd Stage ΔP	8 in. W.C.
Lime-SO_2 Stoichiometry	0.876
SO_2 Removal	87.6% (0.615 #/MM Btu outlet)
Lime Utilization	100%
Particulate Emissions	0.16 #/MM Btu

There were no significant problems in the scrubbing equipment related to scale build-up or fouling. Minor build-ups were observed in the gas inlet area and at the base of the stack. These deposits posed no threat to long term operation.

The overall cost of power, reagents and operating manpower was \$5.07 per ton of coal. This figure was below the estimated cost of \$5.92 per ton and substantially less than the guaranteed cost of \$7.56 per ton.

THE R-C/BAHCO SYSTEM TEST PROGRAM

The major goals of this program were:

- To demonstrate operability of the R-C/Bahco system at RAFB.
- To study system variables to determine optimum and limiting conditions of the system for sulfur dioxide and particulate removal.
- To evaluate and monitor the system over an extended period to obtain maintenance and operating cost data.

Information regarding system operability included the determination of desirable operating conditions and the measurement of system performance in terms of SO_2 and particulate removal. In addition, studies including complete material balances, system stability, and operating requirements were completed. SO_2 and particulate removal efficiencies and the effects of several important system variables including reagent type were determined. A comprehensive evaluation of waste product or "sludge" properties which included dewatering, transport, and disposal characteristics was completed. A complete evaluation of system reliability including an analysis of all downtime was performed. In addition, detailed cost data was obtained for utilities, reagents, operating and maintenance labor and waste disposal.

Preliminary Test Program

The preliminary test program which began shortly after start-up was undertaken to determine the capacity limits of the system, to run preliminary SO_2 and particulate removal tests and to check data acquisition and analytical techniques.

These tests indicated that the gas handling capacity of the scrubber was substantially higher than the design capacity of 55,000 SCFM. Gas flows over 60,000 SCFM were possible without exceeding the capacity of the final mist eliminator. The system operated at pressure drops as low as 12 in. W. C. for both stages to over 30 in. W. C. The pumping rate to the scrubber had to be limited to 3000 gpm, i.e., 15% above the design flow of 2600 gpm to avoid flooding the flue gas inlet manifold when operating at low load conditions. The system operated satisfactorily at slurry solids from 2% to 25% by weight. Particulate emissions were above the required level of 0.16 #/mm Btu when substantial quantities of soot were being formed in the heat plant. Sulfur dioxide removal efficiency was well above the required 83%; levels in the 95% plus range were readily attainable. Data acquisition and analytical techniques were verified during the completion of two overall material balances.

Lime Tests

The results of the lime tests indicate that SO_2 removal is controlled only by the lime-sulfur dioxide stoichiometry. Other operating variables such as gas flow, pressure drops, liquid rates and solids concentration had essentially no effect on SO_2 removal efficiency. The lime tests covered a wide range of flue gas flow rates, 30,000 to 55,000 SCFM, slurry solids concentrations, 2.0 to 15.0%, stoichiometries, 0.6 to 1.08 moles of available CaO per mole of SO_2 and inlet SO_2 concentrations of 400 to 1800 ppm.

Virtually any removal efficiency up to 98 + % can be achieved by adjusting the lime-sulfur dioxide stoichiometry. Virtually no excess lime is required for SO_2 removal efficiencies up to 90%, i.e. SO_2 removal is equal to lime-SO_2 stoichiometry up to this point and with an excess of approximately 10%, 98 + % removal can be achieved.

The fact that SO_2 removal when using lime is not adversely affected by changes in operating variables illustrates the fact that good gas liquid contact is maintained over the entire operating range of the system. This also demonstrates that precise control of these variables is not critical to successful operation.

Limestone Tests

The limestone tests were essentially a duplication of the lime tests. The only major differences were the range of stoichiometries (0.6 to 1.6 moles of available $CaCO_3$ or $MgCO_3$ per mole of SO_2) and inlet SO_2 levels (250 to 600 ppm) investigated. The relatively low SO_2 levels resulted from the low load on the heat plant during the limestone test program.

The results of these tests indicate that slurry circulation rate, in addition to stoichiometry, is important in determing the SO_2 efficiency. The following performance model based on limestone stoichimetry and slurry circulation rate was developed to predict SO_2 removal efficiency.

$$\% \ SO_2 \text{ removal} = (St)^{0.52} \times (L)^{0.55} \quad \text{eq. (5.1)}$$

where: St = limestone-inlet SO_2 stoichiometry

L = second stage slurry circulation rate

The results of these tests indicate that SO_2 removal with limestone above 90% in the R-C/Bahco system is not practical since limestone utilization drops to approximately 60%. This results from the high stoichiometry required to exceed this level of SO_2 removal. However, most industrial boiler applications require SO_2 removal well below the 90% level. For such requirements the use of limestone will accomplish adequate SO_2 removal at a reagent cost substantially below that for lime.

Particulate Tests

Particulate tests were run using both Andersen Impactors and ASME thimbles simultaneously at the inlet and outlet of the scrubber. Collection efficiency as a function of particle size was determined over a wide range of flue gas flow rates and venturi pressure drops. Collection efficiency in the 0.3 to 0.5 micron range was 15.2 to 66.7%, in the 0.5 to 1.0 micron range 27.1 to 86.7%, in the 1.0 to 2.0 micron range 85.3 to 98.9% and in the 2.0 to 5.0 micron range 95.0 to 99.9%. There were substantial variations in observed particulate collection efficiences under similar operation conditions. These variations were caused by fluctuations in the operation of the heat plant which resulted in significant emissions of soot at various times during the particulate test program.

Particulate performance models based on inertial impaction and penetration were developed using these results.

Filtration Rate Tests

Filtration rates varied from approximately 40 to 200 lbs/hr ft^2. Filtration rates for limestone sludges were generally lower than those observed for lime. Lime sludge filter cakes contained approximately 57 to 58% solids and limestone cakes 72 to 76% solids.

Centrifuge Tests

In the centrifugation tests, limestone sludge dewatered to approximately 65 to 67% solids at conditions which produced a lime sludge of 55 to 57%.

Physical/Structural Property Tests

The physical/structural property tests indicated that both sludges when dewatered exhibit similar cohesive and adhesive properties making them somewhat difficult to handle. Limestone sludge samples exhibited higher bearing capacities and higher confined compressive strengths than lime sludge samples.

Leachate Tests

Leachate from both lime and limestone sludges were very similar and were characterized by TDS of 2500 to 3000 ppm, COD values of 6 - 8 mg/l, and contained heavy metals from 5 to 50 ppb.

Overall Systems Monitoring

The monitoring program provided detailed information on operating costs, maintenance costs and operating experience. This information coupled with the results of the test program aided in the determination of optimum operating conditions for the RAFB system.

Operating and Maintenance Costs

During the test period, the gas from the combustion of 27,216 tons of 2.5% sulfur (av.) coal was treated. The total cost for utilities, reagent, supplies and operating labor was $5.07 per ton of coal burned. These costs were projected to be $5.92 per ton of coal burned and a cost ceiling of $7.56 per ton, based on current reagent and power cost, was guaranteed in the contract. Maintenance, labor and materials added $0.21 to the cost for a total of $5.28 per ton of coal burned. An operating cost of $4.06 per ton can be achieved if limestone is used as the scrubbing reagent and fan settings and makeup water consumption are optimized.

The first stage venturi average gas temperature (Tav) and slurry flow rate (L_1) and the second stage slurry flow rate (L_2) were related to the overall penetration for a given size range of particles (d_p) by the following equation:

$$P_o = \exp(a_1 L_1 d_p Tav) \exp(a_2 L_2 d_p) \quad \text{eq. } (6\cdot 10)$$

where a_1 and a_2 are the model's correlation coefficients for the first and second stages respectively.

Analysis of the test data indicated that collection efficiency from 0.3 to 1.0 microns was controlled primarily by conditions in the upper (second stage) venturi and collection efficiency above 1 micron was primarily controlled by conditions in the lower (first stage) venturi.

Slurry Entrainment and Gas Bypassing

During the particulate tests, two phenomena were observed when the system was operated near its capacity limits. The first, called entrainment, which occurs at very low venturi pressure drops, i.e. under 6 in. W.C., involves small droplets of slurry carrying through the second stage mist eliminator and out the stack as indicated by the collection efficiency data and coated sampling probes. The second, called bypassing, is characterized by pulsations in the gas flow through the scrubber and results in low collection efficiency in all particle size ranges. This phenomenon occurs when relatively high pressure drops, i.e. 12 + in. W.C. in either venturi coupled with a slurry flow rate in the scrubber which is less than the minimum required for liquid pickup.

Sludge Characterization Tests

The characterization tests produced data on dewatering rates, physical/structural properties and leachates from lime and limestone based sludges from the R-C/Bahco system at RAFB. A complete description of the tests and results are presented in the report.

Settling Rate Tests

Settling rate tests were conducted on both lime and limestone sludge with and without flocculent. Limestone sludge settled much more rapidly than lime sludge and flocculent addition improved limestone settling rates appreciably. Limestone settling rates were 20-22 lbs/ft^2/day and those for limestone ranged from 164 lbs/ft^2/day without flocculent and 578 lbs/ft^2/day with flocculent.

Operating Experience

As indicated in this report, the system performs satisfactorily in six important areas:

- SO_2 removal efficiency
- Particulate removal efficiency
- Scrubber reliability
- Ease of operation
- Minimal routine maintenance requirements
- Moderate operating costs

However, the system suffered from a considerable amount of downtime. During the test period which included 11,024 hours, there were 4,830 hours of downtime. Most of this downtime, 2,766 hours, resulted from booster fan problems which have been rectified. An additional 1,088 hours were lost due to other auxiliary equipment problems. However, of the total of 3,854 hours lost due to equipment problems, 1,035 hours were due to delays resulting from a lack of spare parts. Heat plant outages and minor system modifications resulted in an additional 507 hours of downtime. The table below summarizes the downtime during the test period.

SUMMARY OF TABLES 8.1 AND 8.2
DOWNTIME DURING THE TEST PERIOD

Category	Downtime Hrs.
Fan	2,766
Auxiliary Equipment	1,088
Heat Plant Outages	388
Modifications	119
Other Items	469
	4,830

The other items which constituted less than 5% of the total period included routine maintenance and freezeup problems which occurred in water and instrument air lines.

Now that the major problems with auxiliary equipment have been cleared up and the freezeup problems have been eliminated, the system should operate 95% or more of the time as it did during the 1976-77 winter including December, January and February.

Optimium Operating Conditions

At the present time local air pollution control requirements limit SO_2 and particulate emissions to 2.2 and 0.16 lbs/MM Btu, respectively. These requirements can be met most economically by the R-C/Bahco system by operating at the conditions listed in Table 9.5 below:

TABLE 9.5 OPTIMUM OPERATING CONDITIONS

	Lime	Limestone
Stoichiometry	0.70	0.75
Second Stage Slurry Rate	2,200 to 2,400 gpm	
Flue gas rates	35,000 to 55,000 SCFM	
First and Second Stage Pressure Drops	7 to 10 in. W.C.	

Present emissions standards will be met at the above conditions. In addition, reagent consumption and power requirements will be minimized with a minimum of operator attention.

SECTION 1

INTRODUCTION

In September 1974, the United States Air Force took a major step in demonstrating the applicability of flue gas scrubbing technology to industrial coal-fired plants. A contract was awarded to Research-Cottrell for an SO_2 and particulate emission control system for the Central Heat Plant at Rickenbacker Air Force Base (RAFB) near Columbus, Ohio. An R-C/Bahco scrubber was selected for this project. (See Figure 1-1) The scrubber, which accomplishes both SO_2 and particulate removal, is based on technology developed by AB Bahco in Sweden and tested world-wide on oil-fired boilers, incinerators and other applications.

In April 1975, when engineering of the system was in its final stages, a second contract sponsored by the USEPA was awarded to Research-Cottrell. The overall objective of this program (Contract No. F33617-75-90100) was to characterize the R-C/Bahco scrubbing system installed at RAFB in terms of its performance, reliability, and economics for SO_2 and particulate control on small coal-fired plants.

The R-C/Bahco system was put into operation in March, 1976, and the characterization program was initiated in April of that year. The first phase involved preliminary testing of the system's operating limits and performance capabilities. The next phase consisted of the following screening and process variable test programs: lime scrubbing of SO_2, limestone scrubbing of SO_2, and particulate removal.

These tests were designed to determine the effect of process variables on SO_2 and particulate removal efficiencies and to provide data for developing mathematical relationships to describe the performance of the R-C/Bahco system.

The final phase of the test program focused on a comprehensive monitoring program to characterize the operation of the system and to develop operating and maintenance cost data. In addition, a program to characterize the sludge produced by the scrubber was carried out.

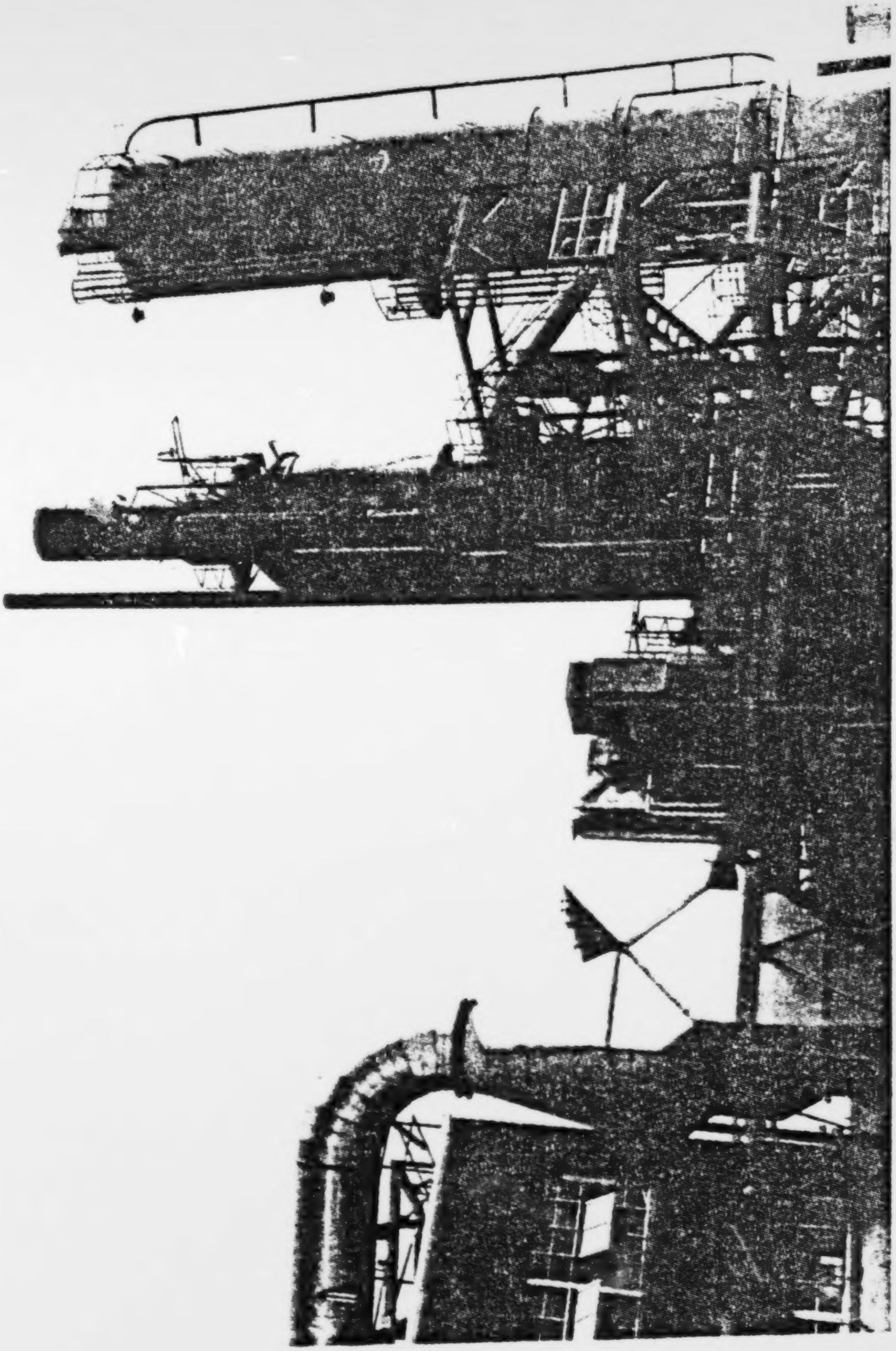

Figure 1-1 The R-C/Bahco Scrubbing System at RAFB

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The test program also included the design, procurement and installation of equipment and instrumentation necessary to execute various phases of the test program. The results of this test program are presented in subsequent sections of this report.

SECTION 2

R-C/BAHCO SCRUBBING SYSTEM

R-C BAHCO SCRUBBING SYSTEM

This FGD test program was carried out at the R-C/Bahco scrubbing system installed at the Central Heat Plant at Rickenbacker Air Force Base near Columbus, Ohio. The heat plant houses eight coal-fired hot water generators with a total fuel burning capacity of approximately 330 mm BTU/hr. These stoker-fired generators burn 2.5 to 3.5% sulfur Ohio coal with an average heating value of 11,300 Btu/lb.

The R-C/Bahco system was designed to treat up to 108,000 ACFM of flue gas generated at the peak winter load of approximately 200 MM Btu/hr. The system which must operate over a relatively narrow range of gas flow, 35,000 to 50,000 SCFM has an essentially unlimited turndown capability for handling flue gas by mixing air with the flue gas at low boiler loads. This allows the system to handle seasonal load variations from 20 to 200 MM Btu/hr, SO_2 concentrations from 200 to 2000 ppm and particulate loadings up to 2 gr/SCFD. In addition, the scrubbing system copes with 100% load increases occurring in as little as an hour's time. Table 2.1 shows scrubber operating conditions on March 30, 1976, these were approximate average load conditions for RAFB.

TABLE 2.1 TYPICAL SYSTEM OPERATING CONDITIONS

Flue Gas	64,000 ACFM@380°F(37,500 SCFM)
SO_2 Concentration	1390 ppm
1st Stage ΔP	10 in. W.C.
2nd Stage ΔP	8 in. W.C.
Lime-SO_2 Stoichiometry	0.876
SO_2 Removal	87.6% (0.615 #/MM Btu outlet)
Lime Utilization	100%
Particulate Emission	0.16 #/MM Btu

PROCESS DESCRIPTION

Hot flue gas from each of the Heat Plant generators is passed into a common flue which contains a by-pass stack. This stack allows makeup air to be drawn into the system at low load to maintain efficient operation of the mechanical collector and scrubber. Flue gas, with or without makeup air, is passed through a mechanical collector to remove coarse particulate matter before entering the booster fan.

This fan forces flue gas into the first stage of the scrubber where it is vigorously mixed with scrubbing slurry in an inverted venturi. In this stage, flue gas is cooled to its adiabatic saturation temperature and SO_2 and particulate are scrubbed from the gas. This partially scrubbed gas rises to the second stage where it is contacted with slurry containing fresh lime to complete the required SO_2 and particulate removal. Gas from the second stage enters a cyclonic mist eliminator where entrained slurry droplets are separated from the gas by centrifugal force to produce an essentially droplet-free effluent.

Pebble lime from a storage silo is slaked and added directly to the slurry in the lime dissolving tank. The resulting fresh lime mixture is pumped to the second stage (upper) venturi to treat the flue gas stream. The slurry flows by gravity from the second stage to the first stage where it contacts hot flue gas entering the scrubber. This countercurrent flow arrangement results in high SO_2 removal and efficient reagent usage.

Spent slurry flows by gravity from the first stage of the scrubber to the dissolving tank. Part of the spent stream leaving this stage is diverted to the thickener where the slurry is concentrated to 35 to 40% solids. Overflow from the thickener returns to the dissolving tank and the underflow is pumped to a Hypalon-lined sludge pond near the Heat Plant.

The slurry and gas streams described above are illustrated in Figure 2-1.

MAJOR EQUIPMENT

The following items, shown in Figure 2-1, constitute the major equipment installed in the R-C/Bahco System at RAFB. A brief description for each item, including its role in the operation of the system, is provided below.

Flue System

The flue system includes individual tie-ins to each of eight boilers. Manual diversion dampers allow for gas flow into the flue system or bypassing through individual stacks. In addition, a stack in the main flue upstream from the mechanical

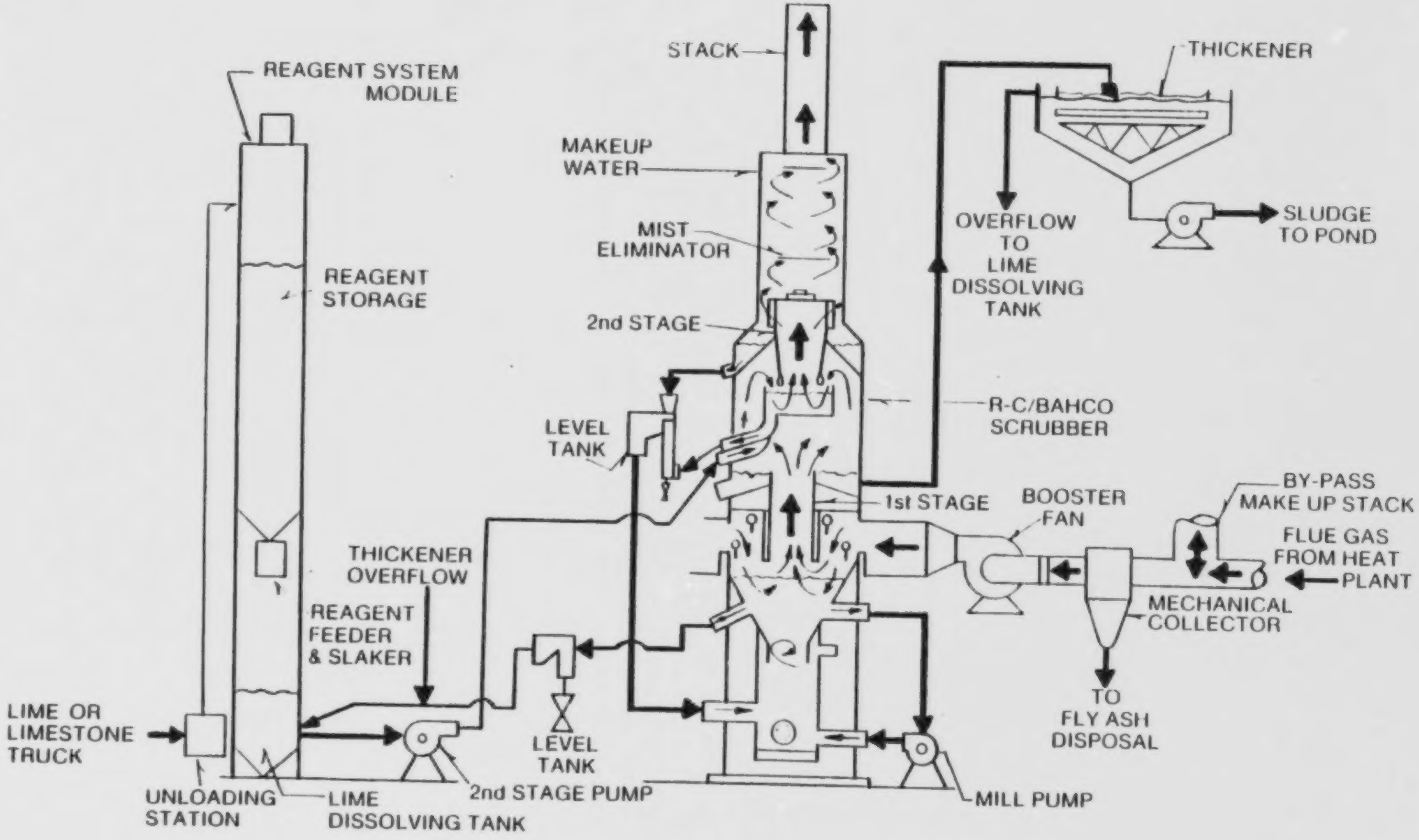
REAGENT SYSTEM MODULE
STACK
THICKENER
MAKEUP WATER
MIST ELIMINATOR
REAGENT STORAGE
OVERFLOW TO LIME DISSOLVING TANK
SLUDGE TO POND
2nd STAGE
R-C/BAHCO SCRUBBER
LEVEL TANK
1st STAGE
BOOSTER FAN
BY-PASS MAKE UP STACK
FLUE GAS FROM HEAT PLANT
THICKENER OVERFLOW
MECHANICAL COLLECTOR
REAGENT FEEDER & SLAKER
TO FLY ASH DISPOSAL
LIME OR LIMESTONE TRUCK
LEVEL TANK
UNLOADING STATION
LIME DISSOLVING TANK
2nd STAGE PUMP
MILL PUMP

Figure 2-1: R-C/Bahco Scrubber System Flow Diagram

collector allows for the addition of makeup air to the gas or bypassing of the scrubber. The flues are insulated for personnel protection and to avoid corrosion when the system is operated with makeup air at low load conditions. A multiport pitot tube is located in the main flue upstream from the mechanical collector to measure gas flow rates.

Mechanical Collector

A Flex-Kleen mechanical collector handles 108,000 ACFM of flue gas at 475°F at dust loads up to 2 gr. per SCF. This collector is located in the main flue upstream from the booster fan.

The Flex-Kleen collector operates at approximately 5 in. w.c. pressure drop at full load and 1.5 in. w.c. at minimum load. The overall efficiency for a combination of the Flex-Kleen collector and the individual collectors is 85 to 95%. A common vacuum type ash handling system is used to convey bottom ash from the stokers as well as the ash from the mechanical collectors to a silo. Ash stored in the silo is removed by truck to a disposal site.

Booster Fan

The booster fan draws flue gas and air mixtures through the mechanical collector and forces them into the R-C/Bahco scrubber. The fan was oversized by 200 H.P., for a total of 700 H.P., to allow for high gas flow rates at pressures up to 30 in. W.C. for the EPA test program. The scrubber normally operates at 15 to 18 in. W.C. and the mechanical collector and flues require an additional 5 in. W.C. at full load.

The gas flow rate is varied to compensate for seasonal load changes by adjusting the fan inlet dampers. In the winter very little air is mixed with the flue gas and in the summer up to two thirds of the flow is makeup air.

In addition to the pitot tube, the fan current draw is used to check the flue gas flow rate.

Reagent System

The reagent system, shown in Figure 2-1, consists of a reagent unloading system, storage bin, feeder, and lime slaker.

The pneumatic unloading system handles 3/4" pebble lime or limestone at a rate of 25 tons per hr. The 120-ton capacity storage bin is equipped with a dust collector, pressure-vacuum relief, level indicator, high and low level alarms, outlet slide gate, and a motor driven live bottom which is activiated by the lime slaker.

The weigh belt feeder is equipped with manual and automatic controls and a totalizer. Either the SO_2 mass flow rate or dissolving tank pH can be used to control the reagent feed rate. The lime slaker includes a water totalizer, grit removal circuit, high temperature alarm, and dust and vapor venting system. The slaker overflows into the lime dissolving tank located directly below.

When limestone is being used as the reagent for SO_2 removal, the slaker is used to wet the limestone prior to its entering the dissolver tank.

Lime Dissolving Tank

The lime dissolving tank, which serves as the surge tank for the entire system, is made of 316L SS. In this tank slaked lime or limestone is blended with spent slurry for recirculation to the scrubber.

R-C/Bahco Scrubber

The scrubber module is an R-C/Bahco size 50 fabricated from 316L SS. This module is approximately twelve feet in diameter by sixty feet high and has a nominal gas handling capacity of 50,000 SCFM.

A fiberglass reinforced polyester (FRP) stack, 5.5 feet in diameter and 20 feet high, is mounted on top of the scrubber. The scrubber module incorporates two inverted fixed-diameter venturis. Each has a corresponding level tank located outside the shell of the scrubber with a manually adjusted weir. The pressure drop for each venturi can be varied over a range of 5 to 15 in. W.C. by adjusting the position of the weir in the appropriate level tank. A fluid mill, which grinds coarse particles in the slurry, is located in the bottom of the scrubber module.

Second Stage Slurry Recycle Pump

The second stage recycle pump circulates slurry through the entire scrubbing system. This pump is rubber lined and is rated at 2600 gpm at 20 psig. A 316 SS shaft sleeve and a water purge in the stuffing box are used to minimize wear and corrosion.

Mill Pump

The mill pump is identical to the second stage slurry pump but it operates at 2000 gpm at 25 psig. This pump is the prime mover for the fluid mill at the base of the scrubber module.

Thickener

A thickener which is 25 feet in diameter and 8 feet in height is used for solids surge capacity, slurry density control, and thickening sludge for disposal.

The tank is Douglas Fir and the rake mechanism is rubber-covered carbon steel. The rake mechanism has a lifting device and a torque sensor with a high torque alarm and cutoff for its protection.

The maximum thickener feed rate is approximately 100 GPM at 10 wt.% solids and the maximum underflow rate is 35 GPM at 25 wt.% solids. The minimum underflow rate is approximately 3.5 GPM at 40 wt.% solids without recycle of solids to the scrubber. Thickener overflow is returned to the lime dissolving tank by gravity.

Sludge concentrated adequately for disposal, 35-40 wt.% solids, is continuously pumped from the bottom of the thickener. A slurry density control provides for recirculation of the sludge to the scrubbing system if the scrubber slurry is below 10% solids. Sludge flow is diverted to the pond for disposal when scrubber slurry solids reach approximately 12%.

Sludge Transfer System

The sludge transfer system includes two thickener underflow pumps and two transfer lines to provide 100% standby capacity. The two underflow pumps are air-operated with replaceable neoprene diaphragms and 316 SS wetted parts. The pumps are capable of pumping up to 40 GPM of sludge at 75 psig.

Quick disconnects are used to hook up these pumps to the thickener and the 1½ in. I.D. polybutylene sludge transfer lines.

Sludge line velocities are maintained between 4 and 6 feet per second by setting the pumping rate at 20 to 30 GPM. The sludge lines run underground inside a sleeve to permit easy removal for cleaning or replacement in the event that it is required.

Sludge Pond

The sludge disposal pond shown in Figure 2-2 is located approximately 700 feet from the scrubbing system. The pond is lined with Hypalon, (chloro-sulfonated polyethylene), and is approximately 450 feet long, 250 feet wide, and 12 feet deep. An

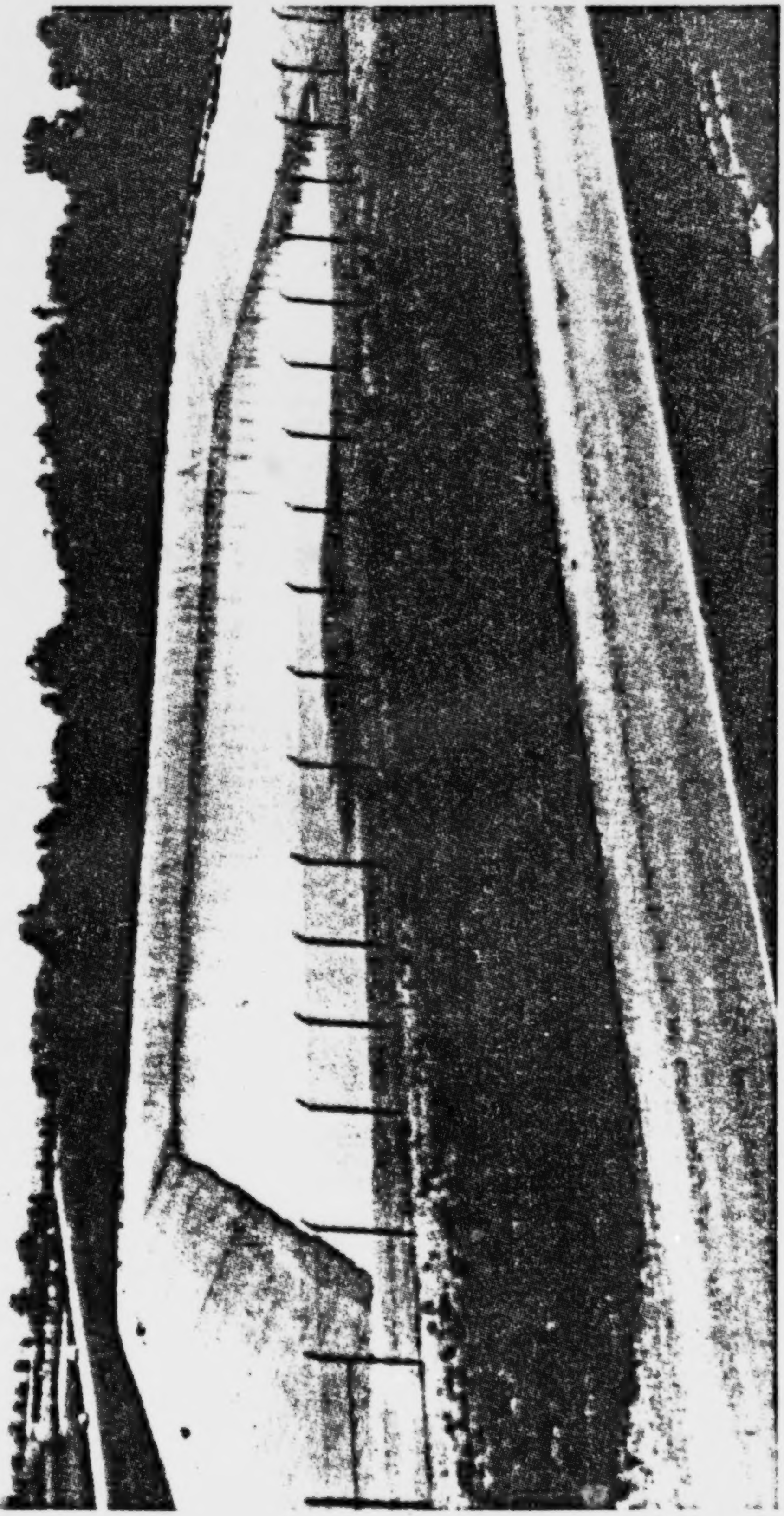

Figure 2-2 Lined Storage Pond at RAFB

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underdrain system which allows ground water to be removed from beneath the liner also serves as a means of detecting any leaks which may occur. The pond was designed to hold sludge produced by scrubbing flue gas from the combustion of 200,000 tons of 5% sulfur coal. The life of this pond is well over five years at present levels of coal consumption.

PROCESS CONTROL

The ability of a flue gas scrubber to accommodate changes in load or other operating parameters is a very important factor in determining its suitability for a given application. For small industrial applications this ability is essential from three points of view. First, the scrubber must be able to reduce emissions of pollutants to acceptable levels over the entire range of flue gas rates generated. Second, accommodations to load changes must be accomplished rapidly without special attention from operating personnel. Third, variations in the scrubbing system's internal processes must not interfere with its ability to perform as required.

Manual Controls

A combination of manual and automatic controls are used to adjust and regulate system variables. The manual mode is used to control variables which do not have to be adjusted frequently or are essentially constant over the entire operating range of the system. Gas flow rate, slurry circulation rate and first and second stage pressure drops are controlled manually.

Gas Flow Rate

At RAFB the gas rate to the scrubber is set manually by adjusting the booster fan inlet dampers. Variations in flue gas rates are accommodated by mixing makeup air with the flue gas to maintain the desired total gas flow rate.

The makeup air system includes an open stack which also serves as a system bypass. No control dampers or other devices are used to regulate makeup air rates. Merely positioning the booster fan damper to obtain the desired total gas flow rate is sufficient for control purposes. Control is maintained, irrespective of the flue gas rate, as long as the flue gas volume is less than the total flow that the booster fan is able to accommodate for the damper position selected. If the flue gas flow exceeds this total rate, gas bypasses through the makeup air stack and activates a temperature alarm to alert the heat plant operators.

Slurry R[illegible]ulation Rates

All slurry circulation rates are manually adjusted and are set to maintain line velocities between 4 and 8 ft/sec. The system is designed to accommodate all loads and load changes without adjusting these slurry circulation rates.

The following loops use this constant flow principle:

- Scrubber mill or first stage slurry recycle loop
- Second stage slurry feed
- Thickener feed
- Thickener underflow (sludge disposal)

An alumina flow nozzle located in the mill in the lower section of the scrubber module is used to control slurry flow in the first stage recycle loop. This nozzle was designed to restrict slurry line velocities to 6-8 ft/sec and to provide the necessary agitation and fluid grinding in the mill.

The main slurry flow from the dissolver tank to the scrubber via the second stage slurry pump was set by checking the pumping rate and setting the pump speed to deliver the desired flow rate. Minor flow adjustments can be made if necessary by adjusting a rubber pinch valve on the second stage slurry pump discharge.

The thickener feed rate is set at 60 to 80 gpm. This flow rate is automatically adjusted via a magnetic flow meter - pneumatic pinch valve flow control loop.

The thickener underflow or sludge flow is adjusted by regulating the air flow to the diaphragm type sludge pump. This rate is set to achieve a thickener under flow concentration of approximately 40% solids and a flow rate of approximately 20 gpm.

Plugging and abrasion of lines was avoided by using slurry lines with maximum pitch, minimum length, a minimum of bends as well as the conservative design velocities (4-8 ft/sec). Traps provided at low points in the level tanks and liquid seals allowed for periodic blow-down of accumulated coarse solids. These coarse solids account for most of the abrasive wear experienced in this type of system.

Pressure Drop

Pressure drops in both the upper and lower venturis are manually adjusted by raising or lowering weirs in level tanks outside the scrubber. Each stage can be adjusted independently to produce a pressure drop from 5 to 15 in. W.C. Raising or lowering the weir causes the slurry level in the scrubber, near the lower edge of the venturi, to rise or fall. The pressure drop in the venturi is directly proportional to the slurry level in the vicinity of the venturi; therefore, weir adjustments produce proportional changes in venturi pressure drop. The pressure drop once set is virtually unaffected by changes in gas flow rate. This insensitivity of pressure drop to gas flow results from the self-adjusting action of the slurry level in each venturi. When an increase in gas flow tends to increase the pressure drop, the slurry level tends to drop because of increased pickup of slurry by the gas stream. This drop in slurry level causes a decrease in pressure drop. When gas flow rate decreases, the slurry level rises, increasing the pressure drop. Thus, the pressure drop is essentially self-compensating as the gas flow varies and tends to stabilize at a value near the inital setting.

This insensitivity of pressure drop to gas flow eliminates the necessity for making adjustments to accommodate the frequent heat plant load changes imposed by the daily needs of the Base.

Automatic Controls

There are three essential automatic controls in the R-C/Bahco scrubber: reagent feed, slurry density, and makeup water or system level.

Reagent Feed

Reagent-SO_2 Stoichiometry is the key variable for controlling SO_2 removal efficiency in this FGD system. Allowable emission rates are exceeded if too little reagent is supplied to the system. If too much is added, excessive reagent costs will be incurred. The reagent feed system at RAFB is designed to maintain a preselected reagent-SO_2 stoichiometry for any load condition and any coal sulfur content. Both the gas rate and the SO_2 concentration to the scrubber are measured continuously. These measurements are combined in a reagent feed rate ratio controller which can regulate feed rate over a range of 20 to 1 to maintain the desired reagent SO_2 stoichiometry.

Slurry Density

Maintaining slurry density in the system is important for two reasons: first, the proper operation of the sludge disposal system requires a relatively constant feed composition, and second, a minimum inventory of solids in the system is required to eliminate scale formation. The slurry density control system at RAFB operates between set points of 10 and 12% solids, 67 and 69 lbs/ft^3 respectively. A sensor monitors slurry density and a controller is activated to allow thickened sludge at 40% solids to flow to the pond when the density reaches approximately 69 lbs/ft^3. Sludge flows continuously to the pond until the density in the system drops to 67 lbs/ft^3. When this point is reached, sludge is recycled to the scrubber and the line to the pond is flushed with water. This switching process is repeated as necessary to maintain system density in the desired range.

Makeup Water

The total water requirement for the system varies directly with load. Evaporative cooling of the flue gas consumes the bulk of the water used.

Water is added to the system at several locations including slurry pump seals and the lime slaker. These items require a relatively constant amount of water irrespective of system load. The balance of the makeup water is added through six spray manifolds located inside the scrubber module. The amount of water added through these sprays is regulated by a level sensor located in the lime dissolving tank. This level sensor activates a programmed controller which adds water in a preselected sequence for a preset time period through each of the six spray manifolds. This controller is designed to start water additions when the level in the dissolver tank reaches the low set point and stop it when the upper set point is reached. Subsequent evaporation and sludge removal cause the level in the dissolver to drop initiating the water addition cycle as necessary to maintain the desired level.

There were a number of problems associated with the electronic instruments installed at RAFB which were all related to improper grounding of milliamp current signal loops. Rewiring these control loops rectified the problems.

SECTION 3

TEST PROGRAM

This section outlines the R-C/Bahco test program from March 1976 through June 1977. The following tests were conducted on the R-C/Bahco FGD system at Rickenbacker AFB:

- Operability/Material Balance
- Lime-reagent process variable
- Lime-reagent verification
- Particulate collection efficiency
- Limestone reagent process variable
- Sludge Characterization
- Scrubber reliability monitoring

TEST DESCRIPTIONS

Operability/Material Balance Tests (May-Sept., 1976)

These tests were conducted to establish the range of operating conditions over which the R-C/Bahco scrubber could be operated and to verify performance at design conditions by completing material balances. The testing schedule is shown in Figure 3-1.

Maximum and minimum gas flow rates, pressure drops, and slurry circulation rates were determined. In addition, preliminary SO_2 and particulate performance data at the limits of the system's capabilities was obtained.

The system was operated at the design gas rate of 50,000 SCFM and complete material balances on calcium, sulfur and total solids were performed.

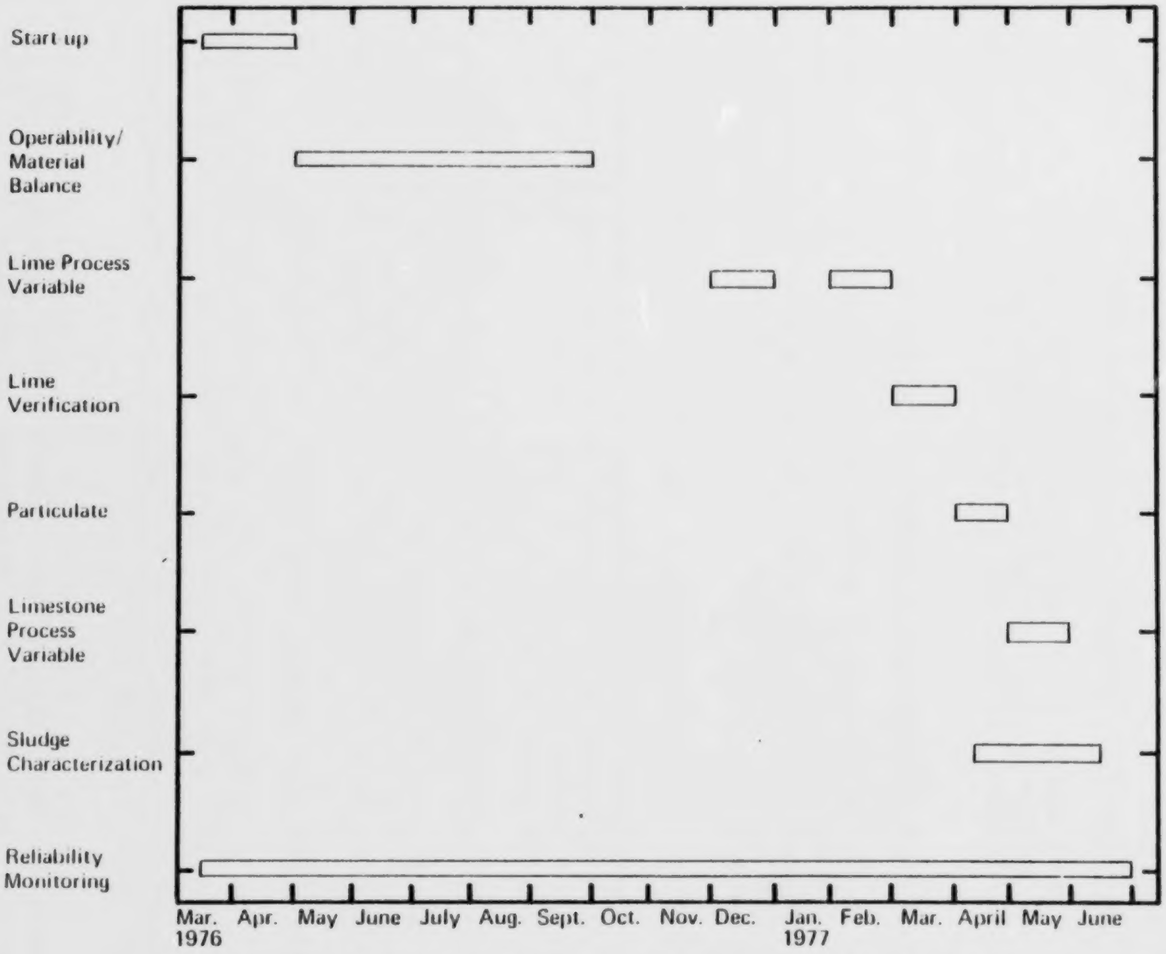

FIGURE 3-1 The Characterization Program Test Schedule

Lime Process Variable Tests (Dec. 1976, Feb. 1977)

These statistically designed tests helped to establish the quantitative effect on SO_2 removal of the following process variables: gas flow rate, first and second stage pressure drops, mill and second stage slurry rates, lime/SO_2 stoichiometric ratio, slurry inventory, and slurry solids concentration.

Lime-Reagent Verification Tests (March 1977)

These tests were run to verify the results obtained in the lime process variable tests and to determine the effect of very dilute scrubber slurry (2% solids) on system performance.

Particulate Collection Efficiency Tests (April 1977)

These tests were a continuation of the particulate tests run in combination with the SO_2 efficiency tests in December and February. Relationships between system variables, including particle size distribution and particulate removal efficiency, were determined.

Limestone Process Variable Tests (May 1977)

The limestone process variable tests were run utilizing the same statistically designed test plan used for lime. The effect of system variables on SO_2 removal efficiency and reagent utilization were determined.

Sludge Characterization Tests (April-May 1977)

Sludge samples generated at RAFB were tested to determine dewatering, transport and disposal characteristics. Samples of sludge from lime as well as limestone scrubbing were tested.

Reliability Monitoring (March 1976 - June 1977)

The R-C/Bahco system was monitored from March, 1976, to June, 1977, to document the system's operating and maintenance history and to obtain data for a cost analysis. Data was gathered on reagent, coal, water and power consumption as well as on operating and maintenance labor.

The results of the various test programs are presented in subsequent sections of this report: The Operability/Material Balance Test results are presented in section 4, the Lime and Limestone Process Variable Test results and the Verification Test results are presented in section 5, the Particulate Test results are presented in section 6, the Sludge Characterization test results are presented in section 7, and the results obtained during the Reliability Monitoring are presented in sections 8 and 9.

DESIGN OF PROCESS VARIABLES TESTS

Identification of Significant Control Variables

SO_2 scrubbing with a slurry containing either lime or limestone may be influenced by many factors including interactions between variables. In order to study the performance of the R-C/Bahco scrubber efficiently, a series of statistically designed experiments was employed. This type of experimental plan maximizes the amount of information obtained from a relatively small number of tests.

The overall system was examined in the first step in this experimental plan to identify the controllable independent variables. Eight variables were selected and incorporated into a statistical screening design. These screening tests were used to determine the significance of the process variables in relation to several dependent (response) variables.

The controlled independent variables selected were:

X_1: Scrubber inlet gas flow rate (SCFM)

X_2: Scrubber first stage pressure drop (in. W.C.)

X_3: Scrubber second stage pressure drop (in.W.C.)

X_4: Slurry rate to the second stage (GPM)

X_5: Slurry rate to the mill (GPM)

X_6: Stoichiometric ratio (moles CaO or $CaCO_3$/mole SO_2 in the inlet gas stream)

X_7: System slurry volume (gals.)

X_8: Slurry concentration (Wt. % solids)

The dependent (response) variables monitored were:

1. Exit gas temperature
2. Outlet SO_2 concentration
3. 1st stage level tank slurry pH
4. 1st stage drop collector slurry pH
5. 2nd stage slurry feed pH (dissolver pH)
6. 2nd stage level tank slurry pH

7. 2nd stage drop collector slurry pH

8. Component concentrations (Wt.% $CaSO_4 \cdot 2H_2O$, Wt.% $CaSO_3 \cdot 1/2\ H_2O$, Wt.% alkali (CaO, $CaCO_3$)

9. 1st stage liquid pick-up

10. 2nd stage liquid pick-up

In addition to the above the inlet SO_2 concentration was monitored for all tests.

Lime Reagent Tests

A test program consisting of twenty-one runs was undertaken to study the SO_2 removal efficiency of the R-C/Bahco scrubber using lime as the scrubbing reagent. The screening test program was a 1/16 fractional factorial of a 2^{8-4} full factorial statistical design.[1] The program was comprised of sixteen combinations of high and low levels of the eight controllable independent variables shown in Table 3.1. Five tests at centerpoint conditions were run to estimate the experimental error. Tests were performed in a random order to minimize the effects of extraneous factors on the experiments. However, in certain cases, randomization required major system changes which would have resulted in substantial testing delays. The test sequence was modified to minimize these delays. Table 3.2 shows the target levels for each of the eight independent variables used in the lime tests.

Limestone Reagent Tests

The use of limestone as an alternate scrubbing reagent for SO_2 removal was investigated in a second series of screening tests. The same independent variables and the same system responses used in the lime tests were studied. Adjustments were made in the levels selected for the independent controllable variables to accommodate system operating limits encountered in the lime test series and to provide for a wider range of stoichiometry to reflect the lower reagent utilization expected for limestone. The adjusted variable levels used for limestone are listed in Table 3.3.

Process Variable Test Procedures

After test conditions were set for each run and had stabilized, usually within an hour, data for all control and response variables was taken. Approximately one hour after the first set of data was recorded a second set was taken. The average values of these results were used in subsequent analyses. Load variations at RAFB cycled in a time span similar to the system's 12 to 24-hour residence time. This fact rendered steady-state

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(1) See $^{K-P}$ Fractional Factorial Designs, Part I, G.E.P. Box and J.S. Hunter, Technometrics, August, 1961, Vol. 3, No. 3.

TABLE 3.1 SCREENING TEST MATRIX FOR THE R-C/BAHCO TEST PROGRAM

Run No.	Variable No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
1		+	+	+	+	+	+	+	+
2		+	+	+	−	−	+	−	−
3		+	+	−	+	−	−	−	−
4		+	+	−	−	+	−	+	+
5		+	−	+	−	−	−	−	+
6		+	−	+	−	+	−	+	−
7		+	−	−	+	+	+	+	−
8		+	−	−	−	−	+	−	+
9		−	+	+	+	−	−	+	−
10		−	+	+	−	+	−	−	+
11		−	+	−	+	+	+	−	+
12		−	+	−	−	−	+	+	−
13		−	−	+	+	+	+	−	−
14		−	−	+	−	−	+	+	+
15		−	−	−	+	−	−	+	+
16		−	−	−	−	+	−	−	−
17		0	0	0	0	0	0	0	0
18		0	0	0	0	0	0	0	0
19		0	0	0	0	0	0	0	0
20		0	0	0	0	0	0	0	0
21		0	0	0	0	0	0	0	0

Note: High target levels are designated by (+) symbols, low levels by (-) symbols and center points by (0) symbols.

TABLE 3.2 TARGET LEVELS FOR LIME TESTS

Target Levels	Gas Rate (SCFM) X_1	1st Stage ΔP, (in. w.c.) X_2	2nd Stage ΔP, (in w.c.) X_3	2nd Stage Slurry Rate, (GPM) X_4	Mill Slurry Rate (GPM) X_5	Lime/SO_2 Stoichi- ometry X_6	Slurry Volume, (Gal) X_7	Slurry Conc., (Wt.%) X_8
High Level (+)	50,000	12	12	2500	2500	1.0	17,000	15
Center Point (0)	42,500	9	9	1750	1750	0.85	15,000	10
Low Level (-)	35,000	6	6	1000	1000	0.7	13,000	5

TABLE 3.3 TARGET LEVELS FOR LIMESTONE TESTS

Target Levels	Gas Rate (SCFM) X_1	1st Stage ΔP,(in w.c.) X_2	2nd Stage ΔP,(in. w.c.) X_3	2nd Stage Slurry Rate, (GPM) X_4	Mill Slurry Rate (GPM) X_5	Limestone/ SO_2 Stoichiometry X_6	Slurry Volume, (Gal) X_7	Slurry Conc., (Wt.%) X_8
High Level (+)	50,000	12	12	2500	2500	1.3	17,000	10
Center Point (0)	42,500	9	9	2000	1750	1.0	15,000	6
Low Level (-)	35,000	6	6	1500	1000	0.8	13,000	2

operation impossible. The effect of this situation was minimized by running tests in as short a time as practical and by subsequently analyzing measurements and samples to determine the actual levels of controlled variables during the tests.

These tests were run by setting the appropriate controlled variables and allowing the system to stabilize. This usually occurred within an hour. An initial set of data was taken at this time and a second set was taken thirty to sixty minutes later. These sets of data were then compared to see if there were any substantial changes. If these were, additional time was allowed for stabilization and new data sets were collected.

Basically employing non-steady state testing facilitated testing at the expense of precise regulation of certain controlled variables, especially limestone/SO_2 stoichiometry. A full range of variable levels was achieved in spite of the inability to preselect them with precision. Analytical tests used during the test program are listed in Table 3.4.

TABLE 3.4 ANALYTICAL TESTS

Method[2]	Sample	Components	Analyzer
TGA	Slurry	$CaSO_3 \cdot \frac{1}{2}H_2O$, $CaSO_4 \cdot 2H_2O$, $CaCO_3$, $MgCO_3$, $Ca(OH)_2$, Loss on Ignition	
Photometric	Gas	SO_2	duPont SO_2 Analyzer
Wet Chemical	Lime	Alkalinity as CaO, Acid Insolubles, Calcium, Magnesium, SO_4, Cl	
TGA	Lime	$CaCO_3$	
Wet Chemical	Gas	CO_2, O_2, CO	Orsat Analyzer
Wet Chemical	Gas	SO_2	EPA Method 6 &R-C Method
Impaction	Gas	Fly ash particle size	Andersen Impactor
ASME & EPA	Gas	Fly ash grain loading	
TGA	Limestone	$CaCO_3$, $MgCO_3$	
Wet Chemical	Limestone	Ca, Mg, total alkalinity, acid insolubles, SO_4	
Wet Chemical	Slurry	Ca, Mg, TDS, SO_4, SO_3, Cl Acid Insolubles, S.G., % solids	
Combustion, etc.	Coal	% S, Heating value, ultimate analysis	
pH Meter	Slurry	pH	Great Lakes pH Probes, Corning Battery-Powered Meter

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(2) See Appendix B for a description of thermogravimetric analysis and a list of the wet chemical and other tests used.

SECTION 4

OPERABILITY/MATERIAL BALANCE TEST RESULTS

R-C/BAHCO SCRUBBER OPERATING LIMITS

The performance of an R-C/Bahco scrubber is measured by its ability to handle variations in flue gas flow rate and temperature, while achieving reductions in SO_2 concentrations and particulate loadings sufficient to meet applicalbe emissions standards. The following scrubber system variables must be evaluated to determine levels which must be maintained to insure compliance with emissions standards.

- Gas Rate
- Slurry Circulation Rate
- First and Second Stage Venturi Pressure Drops
- Slurry Solids Concentration
- Reagent/SO_2 Stoichiometry

A test program was carried out to establish ranges of the above variables for the R-C/Bahco System at RAFB which would produce SO_2 and particulate emissions within the limits allowed by the local regulation. The results of these tests, which are summarized in Table 4.1, were used to select operating conditions in the subsequent process variable test programs. In addition, results from other portions of the overall characterization program which defined system limits are included in Table 4.1.

Gas Rate

The total gas rate to the scrubber must be maintained between 35,000 and 55,000 SCFM. In this range of gas flow, liquid pickup in the venturi results in liquid-to-gas ratios high enough to saturate the gas stream and produce good SO_2 and particulate removal. In addition to inadequate liquid pickup at gas rates below 35,000 SCFM, unstable operation affecting the first stage venturi can occur. At first stage pressure drops over 12 in. w.c., gas flow tends to surge, producing intermittent gas flow through the scrubber. When this occurs, SO_2 and particulate emissions exceed allowable levels.

At gas rates approaching 60,000 SCFM, the capacity of the 2nd stage mist eliminator is exceeded and droplets of slurry entrained by the gas stream are emitted from the scrubber.

TABLE 4.1 R-C/BAHCO SCRUBBER OPERATING LIMITS

Variable	Minimum	Maximum
Gas Rate, ACFM	35,000	55,000
Slurry Circulation Rate, GPM	1,500	3,000
Venturi Pressure Drops/Stage for each stage in. W.C.	6	12
Slurry Concentration, wt.% Solids	2	25
Reagent/SO_2 Stoichiometry Moles Reagent/Moles SO_2 Based on Inlet SO_2 levels		
Lime	0.45	1.05
Limestone	0.55	1.2

Slurry Circulation Rate

The second stage pump circulates slurry through the scrubbing system. A slurry circulation rate of 1500 gpm is required to maintain agitation in tanks, line velocities sufficient to keep solids suspended and adequate flow to the venturis. A slurry rate in excess of 3000 gpm can result in slurry overflowing from the first stage into the inlet ductwork when liquid pickup in the first stage venturi is low.

Slurry flow through various sections of the scrubber is essentially self regulating once the adjustable weirs in the first and second stage level tanks have been set for the desired pressure drops.

Since high slurry circulation rates promote SO_2 absorption with limestone, minimize the potential for solids accumulations and minimize the need to throttle the flow of slurry to the scrubber, the circulation rate should be maintained between 2200 and 2400 gpm.

Venturi Pressure Drop

In each stage, adjustable weirs are used to regulate the pressure drop in the venturis. A minimum pressure drop of 5 in w.c. in the first stage is recommended to maintain sufficient liquid pickup to provide for efficient particulate and SO_2 removal, cooling of the flue gas, agitation in the drop collector and adequate flow velocity in the lines from the drop collector to keep solids suspended. A similar pressure drop limitation applies to the second stage.

If the recommended pressure drop of 12 in. w.c. is exceeded in the first stage, unstable operation can occur. Excessive pressure drop in the second stage, especially at low gas flow rates, results in the emission of slurry droplets from the scrubber. A normal slurry pumping rate of 2400 gpm and weir levels set to maintain 8 - 9 in w.c. pressure drop in each venturi allows the scrubber to accommodate day-to-day load changes without adjustment while maintaining acceptable levels of particulate and SO_2 removal.

Slurry Concentration

The R-C/Bahco system is not sensitive to variation in slurry concentration. The scrubber operated successfully for several months at 25% solids without problems. Concentrations as low as 2% solids did not affect SO_2 removal or scrubber operation. However, when the scrubber is operated at or above average load conditions and the solids concentration drops below 5% the thickener cannot produce a sludge suitable for disposal, i.e. 35 to 45% solids.

Reagent/SO_2 Stoichiometry

The range of the reagent/SO_2 stoichiometry ignoring SO_2 emission requirements is limited by the capacity of the reagent feed system, the SO_2 rate to the scrubbing system and the ability of the scrubber components to withstand corrosion at low pH levels. During the process variable tests, lime stoichiometries varied from 0.36 to 1.08 and from 0.59 to 1.55 during the limestone tests. Minimum levels of 0.45 for lime and 0.55 for limestone are suggested to prevent pH levels from dropping below 4.0 . Maximum levels of 1.05 for lime and 1.2 for limestone are suggested. These levels represent the point at which very little additional SO_2 removal can be obtained by increasing the amount of reagent. In other words, these stoichiometries, when running at optimum scrubber operating conditions, represent the upper limit of SO_2 removal for the system.

Maintaining an optimum stoichiometric ratio is critical if SO_2 emissions are to be kept below the required level of 2.2#/million Btu of coal fired while minimizing reagent costs. In the range of of SO_2 removal required, i.e. 70%, for a 3.5% sulfur coal, when lime is used as the scrubbing reagent, the lime/SO_2 ratio is set at approximately 5% above the minimum ratio of 0.70. This safety factor reduces the possibility that lime feed variations will produce excessive SO_2 emissions but also increases overall operating costs by approximately 2%.

When limestone is used as the scrubbing reagent, larger reagent feed rate variations can be tolerated without substantially altering SO_2 removal efficiency since limestone is not fully utilized in the system. Approximately 5 to 10% of the limestone is unreacted and is recirculated in the slurry. This recirculated limestone acts as a buffer and compensates for substantial short term feed rate variations while maintaining the desired SO_2 removal efficiency. The required SO_2 emission rate of 2.2 lbs/MM Btu can be achieved at a 0.75 limestone stoichiometry.

MATERIAL BALANCES

As part of the preliminary test program, measurements were made to perform material balances on the R-C/Bahco scrubbing system. Overall balances for calcium, sulfur and total solids were completed during a two month period following the startup in March 1976. These balances verified the fact that the R-C/Bahco scrubber was performing satisfactorily and that the methods used to measure critical parameters were accurate. Data from these tests are tabulated in Appendix C.

There are many measurements which must be made to complete an accurate material balance. At the RAFB facility, the accuracy of the following key measurements determined the overall accuracy of the balances performed. An analysis of these measurements resulted in an expected uncertainty of approximately 16% in the material balance.

- SO_2 concentration in the flue gas
- Slurry solids concentrations
- Sludge flow rate to the pond
- Gas flow rate to the scrubber
- Lime feed rate and composition

Material Balance Results

Ideally, material balance tests should be run at steady state conditions for relatively long periods of time to minimize the effects of short term system variations and inherent inaccuracies in the measurements taken. The following procedure was selected since steady state conditions could not be achieved at RAFB due to the outside constraints on the heat plant output and extended testing is economically impractical. Each of the material balances was run over a period of approximately 43 hrs. and approximately twenty measurements of each important variable were taken.

The results of these balances, shown as time averages or rates for the test periods, are presented in Table 4.2. The calcium rates indicated a deficit of 16.2% in the first case and an excess of 4.5% in the second, the sulfur rates in both cases indicated deficits of 16.6 and 13.2% and the solids a deficit of 2.4% and an excess of 12.0% in the second.

Many measurements in the first case were combined to obtain these results. Some of the more important measurements are discussed in detail below. Each measurement has an inherent amount of uncertainty or error associated with it. When these measurements are combined as in the above balances, the total uncertainty is greater than any individual value. The inherent error involved in the material balance measurements were 14.9%[1] for the total solids and calcium, and 16.5% for sulfur. The variations observed in the balances were within the estimated ranges of uncertainty. This indicates that there were no errors which were unaccounted for and the balances were as accurate as could be expected.

SO_2 Concentration

Accurate measurement of the flue gas SO_2 concentration is essential to obtaining meaningful results in an SO_2 removal test program. The system at RAFB utilized a DuPont Photometric analyzer with sintered stainless steel probes for these measurements. Regular calibration using certified SO_2-nitrogen mixtures coupled with the analyzer's inherent reliability normally produced results within the expected range of uncertainty ±3%. However, even the most sophisticated and reliable sampling systems are susceptible to occasional problems that result in inaccurate measurements. A rapid field wet test was developed to verify the measurements obtained from the DuPont analyzer. This method which is described in detail in Appendix B has an expected uncertainty of ± 6%.

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(1) The Uncertainty Analysis Principle used in the program are listed in Experimental Methods for Engineers by B. J. Holman, McGraw Hill, 1966, p. 37 et seq.

TABLE 4. 2 MATERIAL BALANCE RESULTS

Test Period 1976	Calcium #m/hr. In	Calcium #m/hr. Out	% Variation	Sulfur #m/hr. In	Sulfur #m/hr. Out	% Variation	Solids #/hr. In	Solids #/hr. Out	% Variation
5/19 to 5/21	3.34	2.66	-16.2	3.21	2.68	-16.6	411	401	-2.4
5/26 to 5/28	2.48	2.59	+ 4.5	2.91	2.53	-13.2	358	407	+12.0

Notes: Results are presented as hourly averages for the test period including accumulations in system inventory.

Slurry Solids Concentration

Accurate measurements of slurry solids concentrations were necessary to determine the change in the inventory of solids in the scrubbing system as well as the quantity of solids leaving the system.

Both hydrometer (specific gravity) and moisture balance measurements were taken to determine the solids content of slurry samples. Correlations using the results of these measurements were developed to provide a rapid method for monitoring the slurry solids concentrations. The following correlation best represents slurry solids concentration - specific gravity data from 2% to approximately 60% solids.

$$\text{Wt.\% Solids} = 38.1\frac{(S.G.) - 0.973)}{(S.G.)} \qquad (4.1)$$

The following linear relationship was developed for 5% to 25% solids.

$$\text{Wt.\% Solids} = 140.6\ (S.G. - 1.0196) \qquad (4.2)$$

The slurry solids and specific gravity data used to develop the correlations in Figure 4-2 are listed in Table 4.3. An examination of the results in Figure 4-2 indicate that there are substantial variations between predicted and observed values of slurry solids concentrations. These variations are due mainly to differences in the chemical composition of the solids since there are substantial difference in specific gravity between different solid species.

In order to obtain accurate data for the material balance, test samples were routinely analyzed on a moisture balance. which has an expected uncertainty of ± 3%.

Sludge Flow Rate

The sludge flow rate was measured by periodically taking samples from the sludge line at the pond. The sludge flow rate was determined by weighing a sample collected in a known time period. The average of the observed rates and the total pumping time, which was accumulated on a totalizing timer on the control panel, were used to determine the total quantity of sludge leaving the system. These rates had an expected uncertainty of approximately ± 2%.

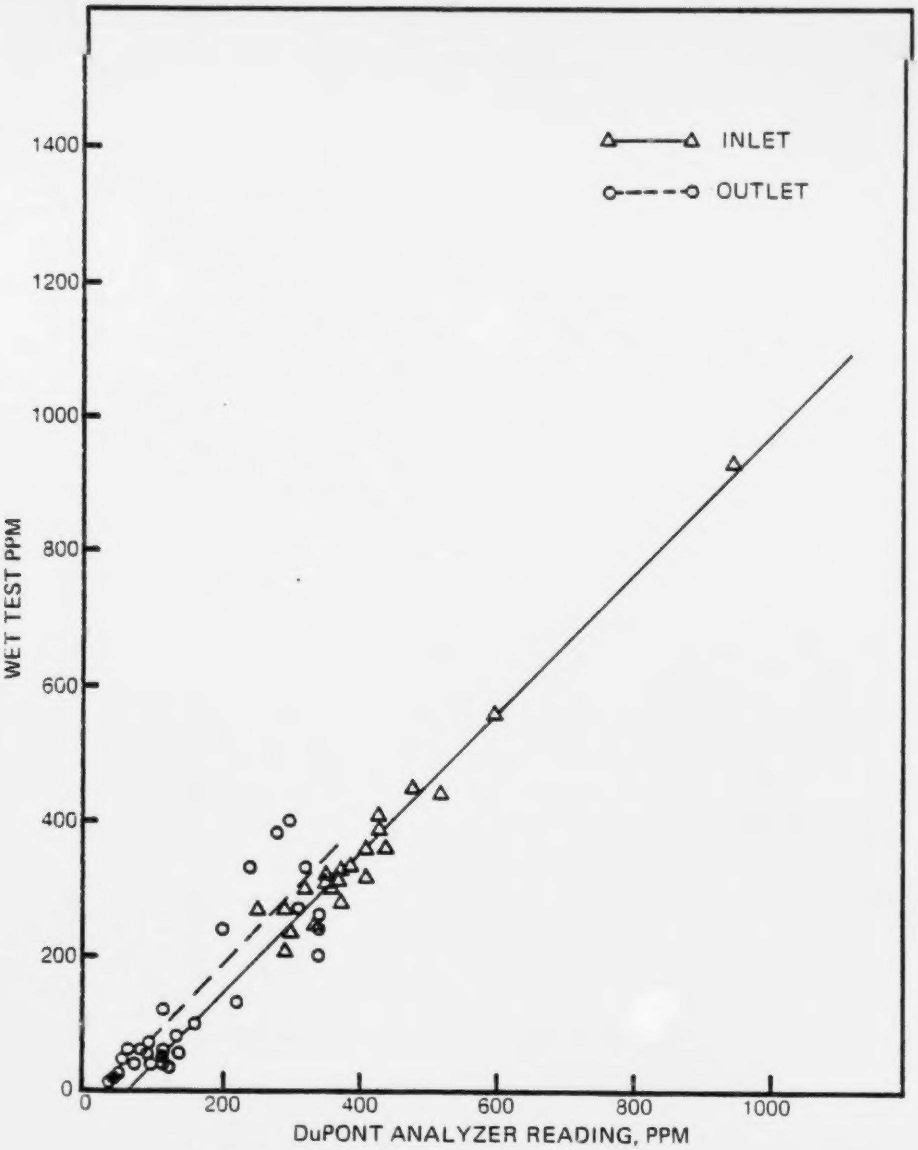

FIGURE 4-1: Verification of inlet and outlet SO_2 concentration data.

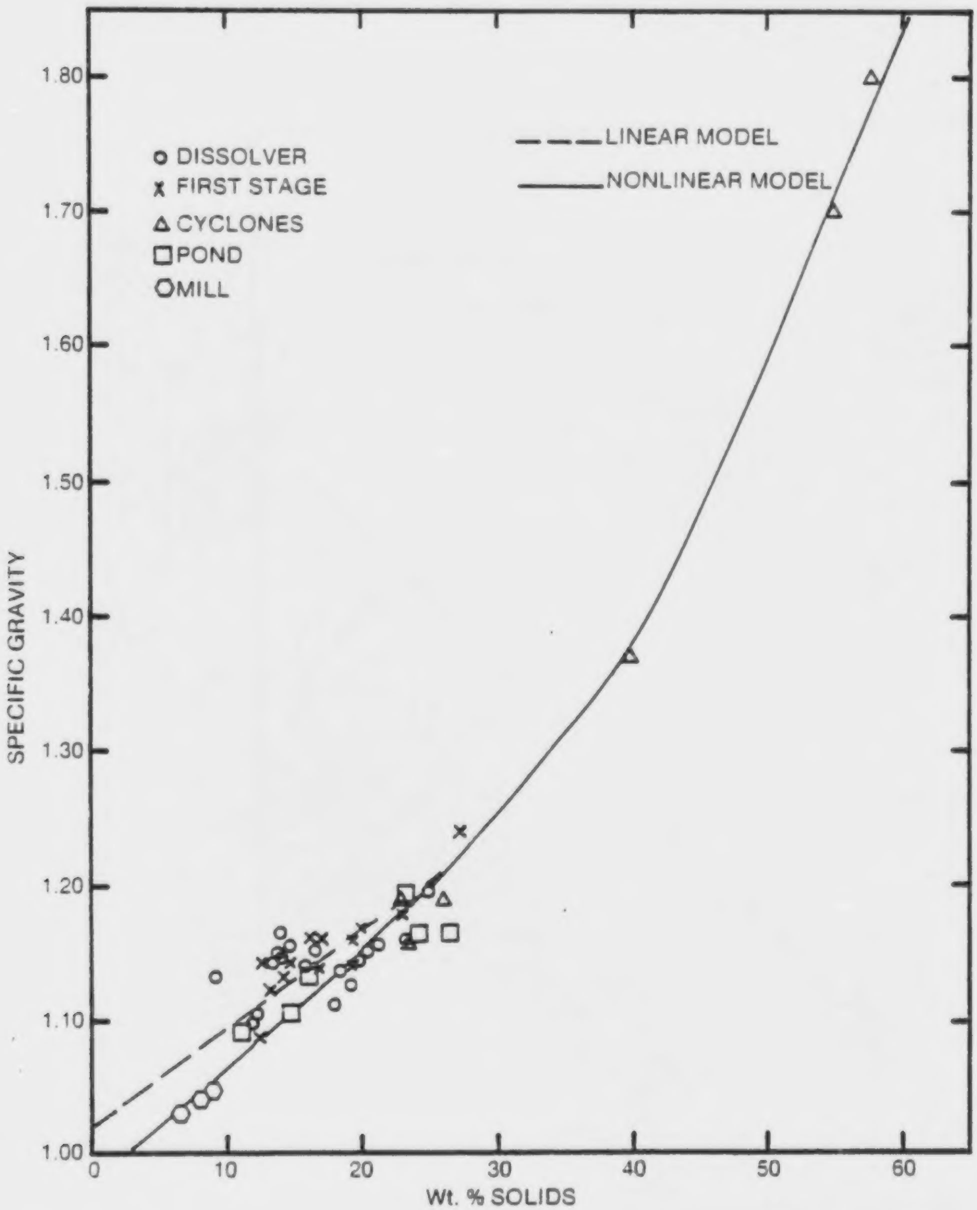

FIGURE 4-2: The relationship between slurry solids concentration and specific gravity.

TABLE 4.3 SLURRY SOLIDS CONCENTRATION AND SPECIFIC GRAVITY

Location	Hydrometer Specific Gravity	Moisture Balance % Solids
Dissolver	1.195	24.8
Dissolver	1.144	20.0
Dissolver	1.160	23.1
Dissolver	1.132	17.7
Dissolver	1.118	17.9
Dissolver	1.136	18.3
Dissolver	1.151	20.4
Dissolver	1.156	21.1
1st stage seal	1.238	27.3
1st stage seal	1.181	22.1
1st stage seal	1.168	19.7
1st stage seal	1.164	16.6
1st stage seal	1.161	16.3
1st stage seal	1.142	19.3
1st stage seal	1.161	19.2
Dewatered slurry	1.800	58.0
Dewatered slurry	1.160	23.3
Dewatered slurry	1.700	55.0
Dewatered slurry	1.190	23.0
Dewatered slurry	1.370	40.0
Mill	1.032	6.5
Mill	1.043	7.9
Mill	1.047	8.5

Gas Flow Rate

The determination of gas flow rates was essential for successful completion of the material balance tests. The flue system at RAFB was designed to accommodate existing site conditions at a minimum cost. As usual, an ideal location for gas flow measurements was lacking. In order to minimize the uncertainty in measuring gas flow rates two independent methods were utilized. A multiport pitot tube was installed in the flue system downstream from the flue gas inlets in the longest straight run available. In addition fan differential pressures and fan motor current readings were used in conjunction with their respective performance curves[2] to provide an independent measurement of gas flow rates.

The gas flow data obtained from these two methods of measurement are listed in Table 4.4 and plotted in Figure 4-3.

An inspection of Figure 4-3 indicates that the fan flow data verify the measurements made with the pitot tube. These flow measurements had an expected uncertainty of ± 5%.

Lime Feed Rate and Composition

The amount of reagent added to the system and its chemical composition are essential elements in completing an accurate material balance. Lime was fed to the system via a weigh belt feeder. For these tests the feed rate was set manually to minimize variations. Samples were taken from the discharge of the feeder at regular intervals to check the feed rate and to obtain samples for subsequent chemical analysis. Table C.2 in Appendix C contains the chemical analyses of the lime samples taken. The lime feeder calibration curve is also included in Appendix C, Figure C. The expected uncertainty in the lime feed was approximately ± 2%.

TABLE 4.4 COMPARISON OF GAS FLOW MEASUREMENT TECHNIQUES

				Gas Flow Rate, SCFM X 10^{-3}	
Run #	Scrubber Inlet Temp. (^{o}F)	Fan Current Draw (amps)	Pitot Tube ΔP (IWC)	Multiport Pitot Tube Flow Data	Fan Flow Data
14	260	95	1.02	58	56
5	227	99	1.14	63	60.2
24	270	90	0.92	55	53.9
10	240	91	0.92	56.5	54.6
15	290	78	0.56	42.5	44.8
7	315	67	0.44	36.8	35.8
30	249	66	--	30.4	33.8
22	327	59	--	26.8	28.0
1	213	70	--	44.1	38.4
9	281	78	--	45.1	43.8
35	245	87	--	50.9	50.4
33	267	85	--	51.6	49.5

Note:

This data has been corrected by standard conditions, 14.7 psia and $32^{o}F$.

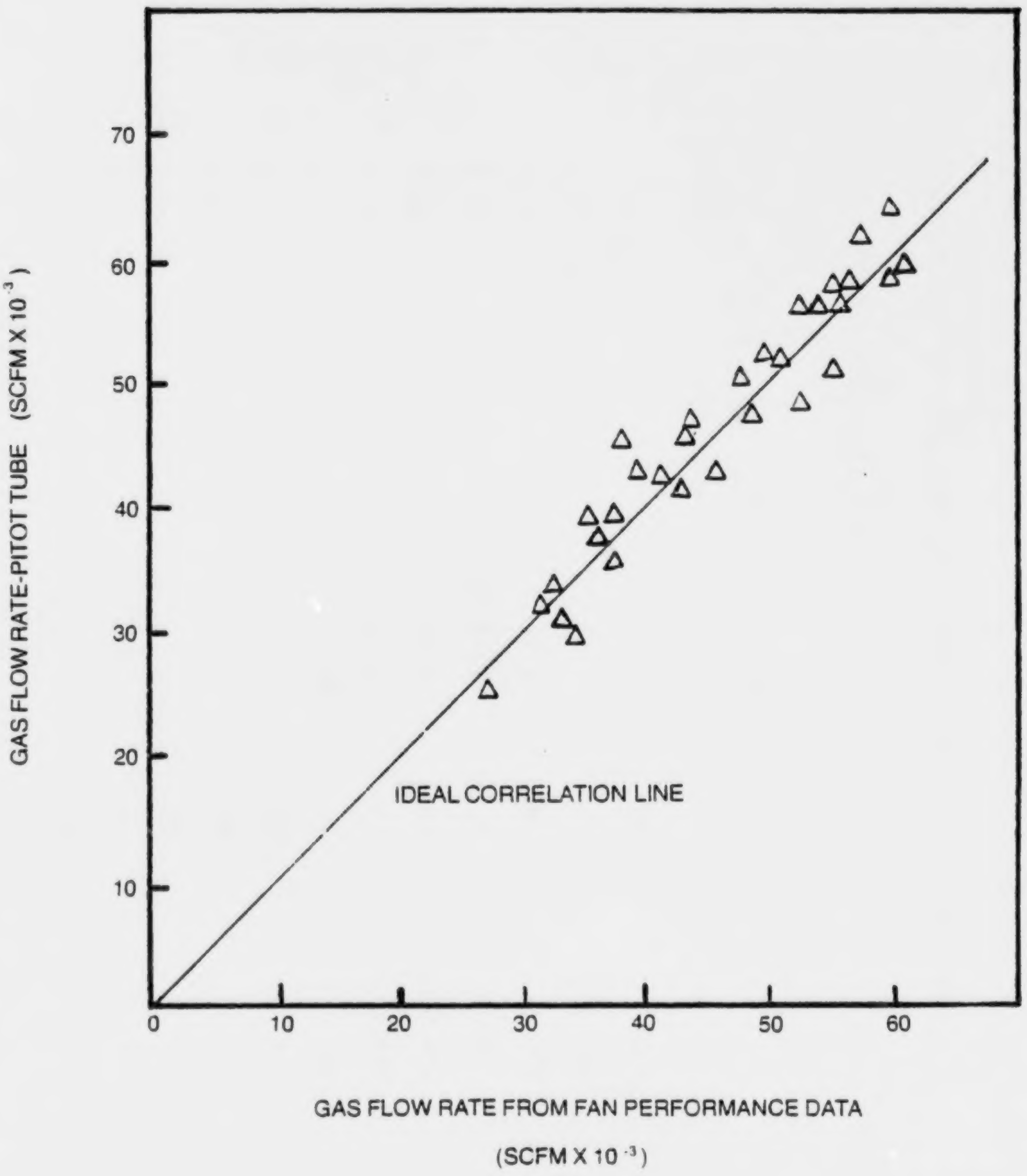

FIGURE 4-3: A comparison of gas flow rates derived from fan performance data and pitot tube measurements.

SECTION 5

SO_2 REMOVAL TESTS

PRELIMINARY SO_2 REMOVAL TESTS

Initial SO_2 removal tests confirmed the high performance capability of the R-C/Bahco scrubber for SO_2 removal. The removal efficiencies observed, 87 to 99%, were higher than the 84% required to comply with the State regulation of 1.0 lb. SO_2/MM Btu heat input initially in effect. Since then, the requirement has been changed to 2.2 lb. SO_2/MM BTU requiring 69% SO_2 removal. Table 5.1 presents the SO_2 removal data collected during startup and early operation. Figure 5-1 illustrates the effect of lime/SO_2 stoichiometry on SO_2 emission rates. Emission rates below 0.10 lbs. SO_2/MM BTU were readily attained at lime/SO_2 stoichiometries of 1.0 to 1.1. In these tests, inlet levels of 300 - 500 ppm were reduced to less than 10 ppm in the outlet gas stream. Virtually complete lime utilization was attained at SO_2 removal efficiencies up to approximately 90%. Lime utilization between 90 and 95% was achieved at SO_2 removal efficiencies in the 97 to 99% range. For these tests, EPA Method 6 was used to determine SO_2 concentrations in the scrubber outlet gas. A DuPont SO_2 analyzer was used to measure inlet concentrations.

LIME SCREENING TESTS

The lime screening tests, as outlined in Section 3, were conducted to identify variables which have a significant effect on SO_2 absorption. In a series of 21 tests conducted in December 1976 and February 1977, eight variables which were susceptible to independent control were screened. Table 5.2 shows average values for the three levels selected for each of the eight variables studied. Some difficulties were encountered in attaining the precise levels planned for certain variables. A comparison between these values and values listed in Table 3.2 indicates that the low levels of 1st and 2nd stage pressure drops and slurry pumping rates were different from the target levels. The low levels of pressure drop were difficult to achieve because they were too close to the lower limits of the system in certain cases. The pumping rates varied from the desired levels because variations in the system volume changed conditions on the suction side of the 2nd stage slurry pump. The levels achieved, however, were satisfactory for the purposes of the screening study since

TABLE 5.1 SO_2 REMOVAL EFFICIENCY DATA

1976 Date	Coal Sulfur Content	Coal Firing Rate (MM BTU/hr.)	Inlet SO_2 Concentration (ppm)	Outlet SO_2 Concentration (ppm)	SO_2 Removal Efficiency (%)	SO_2 Emission Rate (lbs./MM BTU)	Lime Utilization (%)
3/30	3.24	132.2	1,392	156	87.6	0.621	100.0
4/8	3.24	115.2	1,200	45	95.7	0.21	94.0
5/19	3.25	47.9	454	24	94.4	0.29	98.8
5/26	2.64	54.0	555	5	99.0	0.045	90.3
5/26	2.64	52.8	489	8	98.2	0.084	90.5
5/26	2.64	43.3	401	8	97.9	0.095	91.2
5/27	2.01	44.8	327	5	98.3	0.061	94.2
5/27	2.01	44.3	323	5	98.2	0.061	95.4

Note: Removal efficiencies were corrected for increased outlet gas volume due to water evaporation in the scrubber.

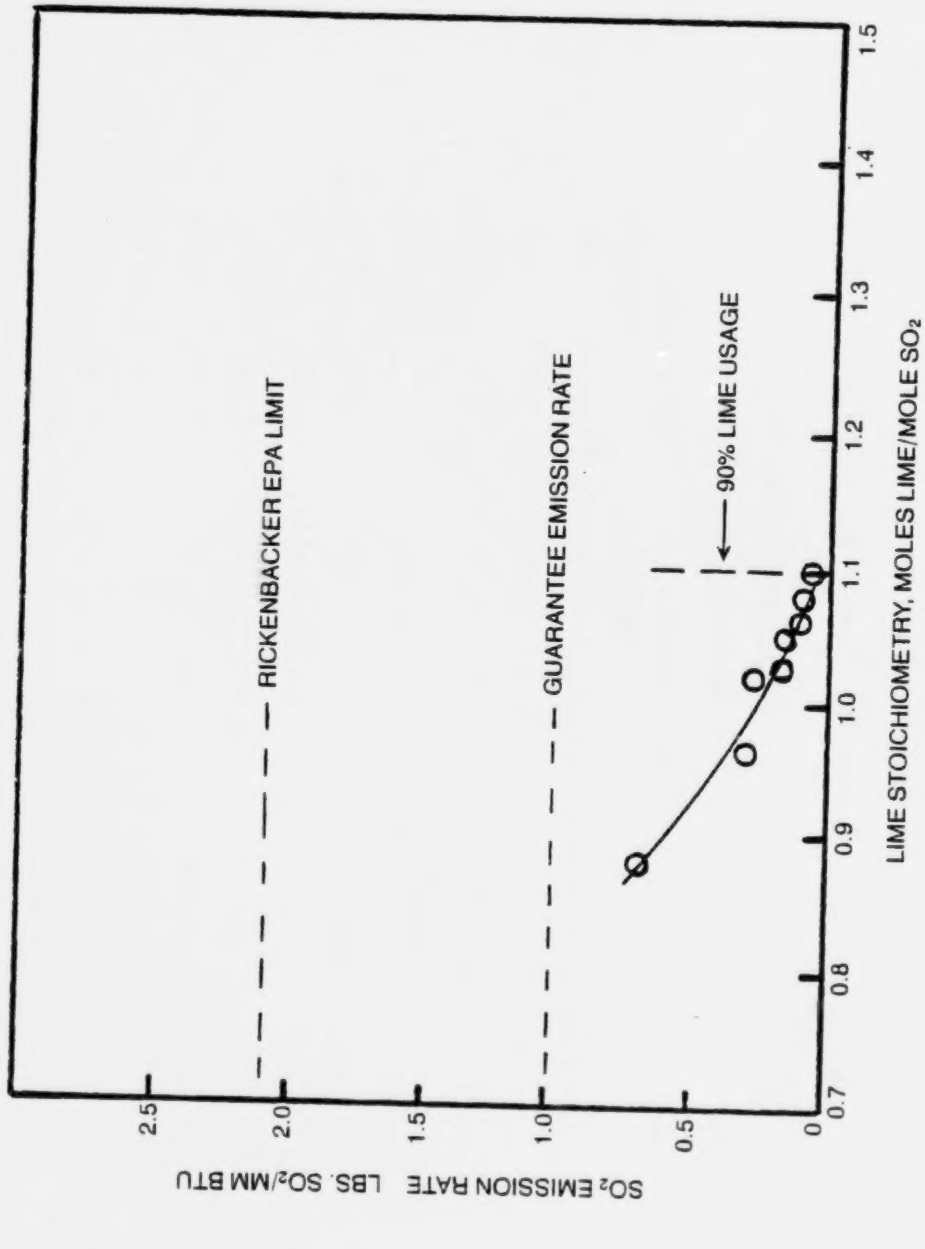

FIGURE 5-1: The relationship between SO_2 emission rates and lime stoichiometry.

TABLE 5.2 LIME SCREENING TEST VARIABLES LEVELS - HIGH, CENTER, AND LOW POINT MEAN VALUES AND STANDARD DEVISIONS

	VARIABLE	HIGH LEVEL		CENTER POINT		LOW LEVEL	
		MEAN	STD. DEV.	MEAN	STD. DEV.	MEAN	STD. DEV.
x_1	Inlet Gas Flow Rate , SCFM	50,680	1548	42,000	620	35,420	828
x_2	1st Stage ΔP, in. W.C.	11.2	2,85	8.2	1.3	8.3	2.8
x_3	2nd Stage ΔP, in. W.C.	11.9	0.88	8.1	0.74	7.25	2.0
x_4	2nd Stage Slurry Pump Rate , GPM	2,703	318	2,342	377	1,903	383
x_5	Mill Pump Rate , GPM	2.024	233	1,476	150	1,258	148
x_6	Stoichiometry	0.992	0.06	0.872	0.16	0.61	0.13
x_7	Scrubber Volume, gal.	16,800	1255	15,540	1155	13,011	1715
x_8	Slurry Conc., % solids	14.06	2.24	10.12	1.00	6.21	1.08

the differences between the high and low levels were sufficient to determine significant effects. The intermediate levels provided information to determine the inherent variability of the test data. The data obtained during these test is summarized in Appendix D.

The following system responses were monitored during the lime screening tests:

- SO_2 removal efficiency
- First stage venturi liquid pickup
- Second stage venturi liquid pickup
- Slurry pH
- Slurry alkalinity

Significant Relationships

The results of the statistical analysis of the screening tests are presented in Table 5.3 Independent variables which were found to have a significant relationship with a system response have a check (✓) in the appropriate row in the table. The following relationships between independent variables and system responses were determined.

SO_2 Removal Efficiency

SO_2 removal efficiency is the most important response variable studied in the screening tests. Lime/SO_2 stoichiometry, as indicated in Table 5.3, is the only variable of significance at the 95% confidence level. Table 5.4 presents SO_2 removal efficiencies determined in each of the screening tests along with lime/SO_2 stoichiometry, lime utilization and liquid pickup in each of the R-C/Bahco scrubber venturi stages. Over a range of SO_2 removal efficiencies from 36% to almost 99%, lime utilizations of over 90% were achieved under all process conditions investigated.

First Stage Liquid Pickup

First stage liquid pickup is significantly influenced by first stage venturi pressure drop and by second stage slurry pumping rate, i.e., the total slurry flow rate to the scrubber. Liquid pickup is normally controlled only by the venturi pressure drop in the R-C/Bahco scrubber. However, the first stage liquid pickup at high pressure drops exceeded the slurry feed rate when the rate was set at low values. Under these conditions the liquid pickup was limited by the slurry feed rate.

TABLE 5.3 SCREENING TEST RESULTS

	Independent Variables							
	Inlet Gas Flow Rate	1st Stage ΔP	2nd Stage ΔP	2nd Stage Slurry Flow Rate	Mill Pump Rate	Stoichiometry	System Volume	Slurry Conc. (% Solids)
SO_2 Removal Efficiency	No effect	No effect	No effect	No effect	No effect	✓	No effect	No effec
1st Stage Liquid Pickup	No effect	✓	No effect	✓	No effect	No effect	No effect	No effect
2nd Stage Liquid Pickup	No effect	No effect	✓	No effect	No effect	No effect	No effect	No effect
1st Stage Drop Collector pH	No effect	No effect	✓	No effect	No effect	✓	No effect	No effect
Total Alkalinity Scrubber Slurry	No effect	No effect	No effect	No effect	No effect	✓	No effect	✓

Note: A confidence level of 95% was selected for the analysis of the lime screening tests.

TABLE 5.4 LIME SCREENING TEST DATA SUMMARY

Stat. Test No.	Run No.	Stoichiometry Lb. Moles Lime/ Lb. Moles SO_2	1st Stage Liquid Pick-up, GPM	2nd Stage Liquid Pick-up, GPM	%SO_2 Removal Efficiency	% Lime Utilization
1	4	0.98	1400	840	95.4	96.9
2	14	0.92	750	660	87.4	95.3
3	16	0.66	1050	300	65.8	100.0
4	5R	0.65	1110	90	64.8	99.1
5	8	0.36	1170	750	36.0	100.0
6	13	0.80	600	1050	78.8	97.9
7	12	0.99	1050	600	94.6	95.2
8	9	0.97	720	640	92.7	95.9
9	14R	0.54	1080	1080	54.5	100.0
10	7R	0.60	750	600	59.8	100.0
11	6	0.93	1080	360	92.5	99.7
12	15	1.06	780	450	98.2	92.5
13	18	1.08	1110	1260	98.7	91.4
14	3	1.00	450	900	96.8	96.5
15	2R	0.60	1020	210	59.6	100.0
16	19	0.67	360	150	63.4	95.1
17	1	0.94	1200	600	89.4	95.5
18	10	0.99	1050	570	95.6	96.5
19	11	0.98	1080	600	93.3	95.6
20	20	0.60	820	300	57.8	95.7
21	21	0.86	900	300	82.3	96.3

LIME VERIFICATION TESTS

Since the screening tests indicated that only lime/SO_2 stoichiometry controlled SO_2 removal efficiency, a series of tests was conducted to verify this finding. The effects of stoichiometry, gas flow rate, and mill pump rate on SO_2 removal were studied in more detail. In addition, the effect of low slurry solids concentration, namely 2 wt.%, on SO_2 removal was investigated. The above variables were selected for these tests because of their possible contribution to SO_2 absorption based on conventional mass transfer theories[1] which relate gas absorption accompanied by chemical reaction to both gas phase and slurry phase parameters.

Verification Test Results

As Figure 5-2 shows, a nearly linear relationship exists between lime/SO_2 stoichiometry and SO_2 removal efficiency. Lime utilization approached 100% in the verification tests in the range of stoichiometry from 0.3 to 0.9 moles lime/mole SO_2 and dropped gradually to 90-95% as SO_2 removal approached 100%. These results confirmed the screening tests results and indicate that essentially any SO_2 removal efficiency desired can be achieved by controlling by the lime/SO_2 stoichiometry.

Over the range of conditions studied, gas flow rate, mill pump rate and slurry solids concentration had no effect on either SO_2 removal or lime utilization as indicated in Table 5.5 and Figures 5-2 and 5-3.

The only negative effect that was observed when operating at 2% solids related to the capacity of the sludge disposal system. The thickener was designed to handle a 10% solids feed at 60 to 100 gpm and produce a 40% solids underflow. In order to produce a 40% solids underflow at the load conditions which existed during the verification tests at 2% slurry solids concentration a 200 gpm feed rate would have been required. In order to accommodate this feed rate, an increase in thickener volume of 100% would have been required. Since neither of these increased requirements was possible, a dilute underflow in the range of 10 to 15% solids was produced.

During the lime tests reagent purity was checked on a regular basis as a part of the data package needed for this portion of the test program. Although Air Force specifications required a minimum of 83 wt.% CaO, our laboratory analyses showed that the actual levels varied from 74 to 95%[2]. During the December

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(1) D. V. Danckwerts, Gas Liquid Reactions, McGraw Hill, 1970.

(2) See Appendix E for reagent and coal specifications and analyses.

TABLE 5.5 LIME VERIFICATION TEST RESULTS

RUN NO.	STOICHIOMETRY MOLES LIME/ MOLE SO_2	GAS FLOW RATE SCFM	MILL PUMP RATE, GPM	SLURRY SOLIDS CONCENTRATION WT. %	% SO_2 REMOVAL	% LIME UTILIZATION
23	0.572	62,900	1,150	17.7	56.7	99.08
24	0.417	64,300	1,750	16.1	41.3	98.92
25	0.565	65,,150	2,300	18.0	55.9	-
29	0.674	47,900	1,600	3.2	65.5	97.22
30	0.698	53,200	2,400	2.4	68.4	98.06
31	0.710	65,400	1,550	2.4	69.0	97.22
32	0.901	65,600	2,200	9.2	88.2	97.90
33	0.985	72,100	1,700	10.3	96.6	98.04
34	0.746	68,700	2,150	10.6	73.2	98.19
36	0.944	70,900	2,200	11.5	92.5	97.97
37	0.930	74,400	2,150	9.8	92.1	98.13

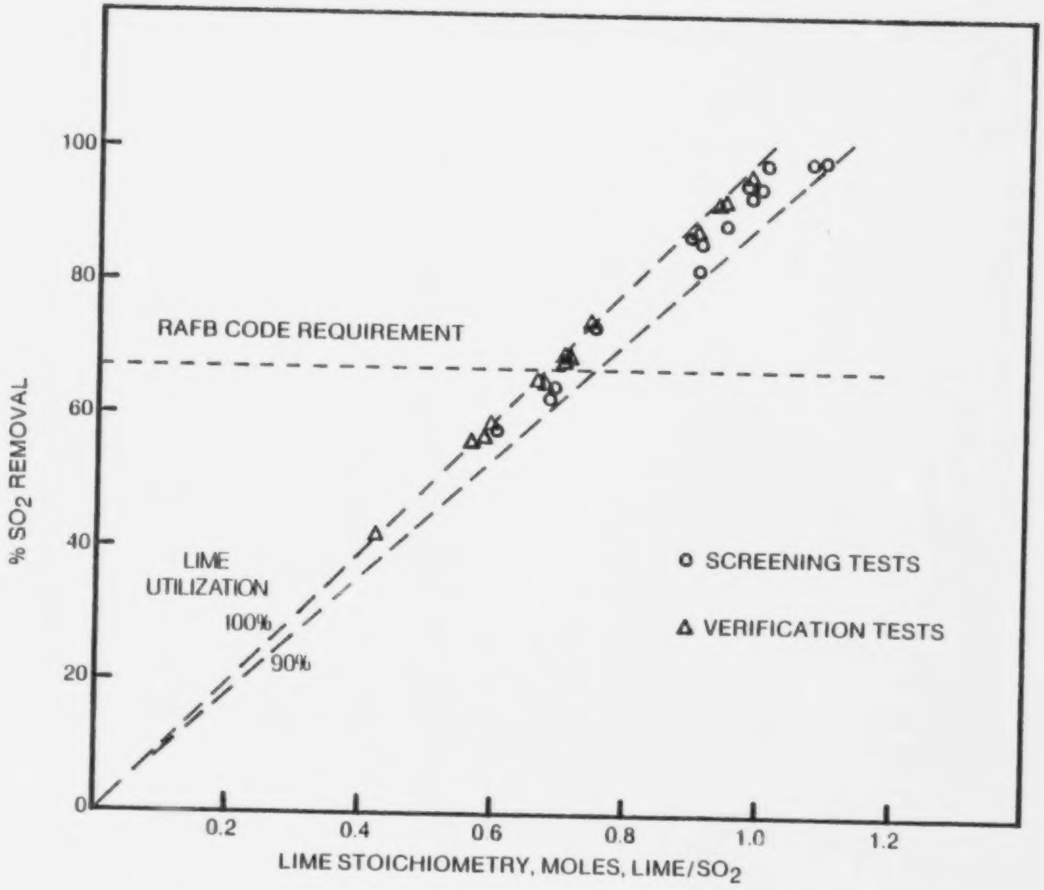

FIGURE 5-2: SO_2 removal efficiency as a function of lime stoichiometry.

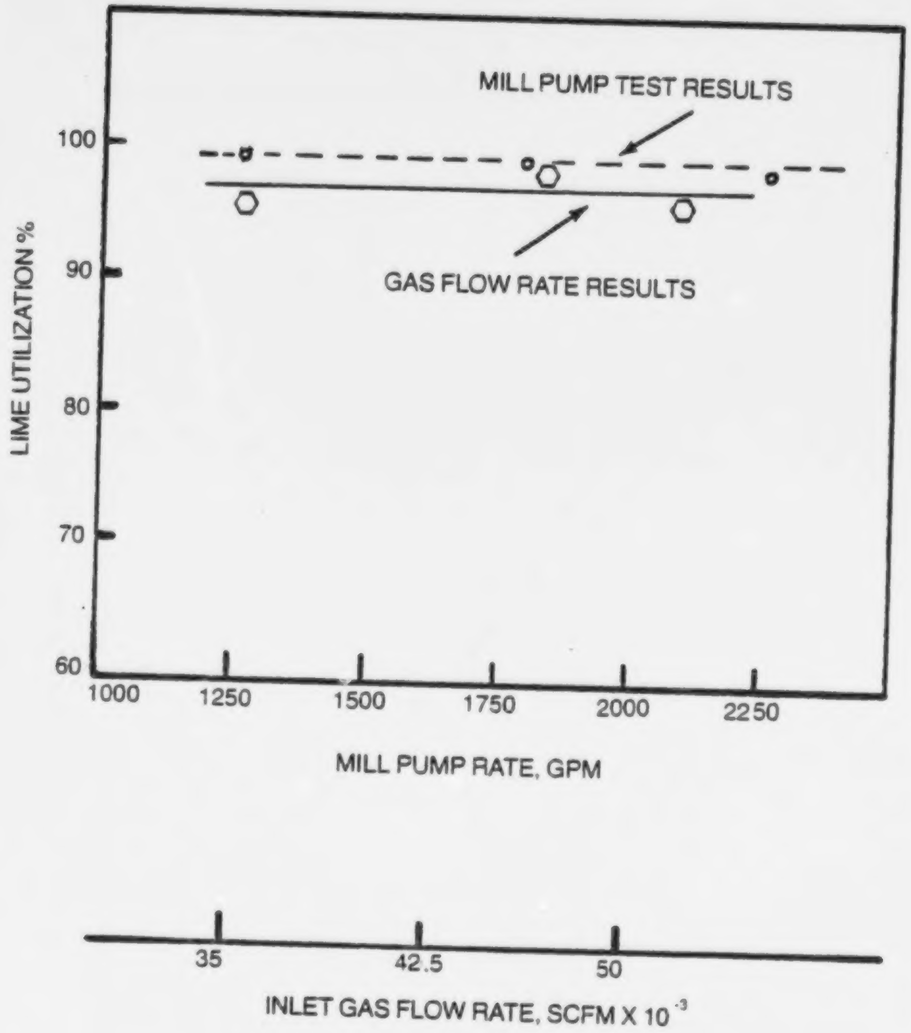

FIGURE 5-3: SO_2 verification test results.

1976 tests, when low CaO content lime was utilized in the scrubber, the reagent feed rates selected resulted in lower lime/SO_2 stoichiometries than desired. This became evident only after analyzing the lime samples after the tests were performed. These variations in reagent purity account for some of the variations observed between target stoichiometries and the actual levels achieved in the lime tests.

Conclusions

Lime/SO_2 stoichiometry is the controlling factor in determining SO_2 removal efficiency. Virtually any desired SO_2 removal efficiency can be achieved in the R-C/Bahco scrubber, when using lime, simply by adjusting the lime/SO_2 stoichiometry.

Lime utilization approaching 100% is achieved at stoichiometric ratios up to about 0.9. At stoichiometric ratios up to 1.1, producing up to 99% SO_2 removal, lime utilization is above 90%.

LIMESTONE PROCESS VARIABLE TESTS

In May 1977, a series of limestone process variable tests, modeled after the lime screening test design, were conducted. A program of twenty-one runs in which eight operating variables were investigated was completed.

Limestone Test Results

The results of these process variable screening tests listed in Table 5.6 indicate that limestone/SO_2 stoichiometry and second stage slurry pumping rates control SO_2 removal.

The following mathematical model was developed to predict SO_2 removal efficiency when limestone is used as the scrubbing reagent:

$$\%SO_2 \text{ removal} = (St)^{0.52} \times (L)^{0.55} \qquad (5.1)^{3}$$

where:

St = stoichiometry, moles of $CaCO_3$ per mole SO_2 in the inlet gas and

L = second stage slurry flow rate, GPM.

Figure 5-4 shows predicted performance using Equation (5.1) and observed SO_2 removal data. Figure 5-5 provides for a more direct comparison between the observed SO_2 removal efficiency and the value predicted from Equation (5.1). If there were no inherent errors in the measurements used to determine SO_2 removal efficiency and Equation (5.1) predicted SO_2 removal

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(3) A General Electric multiple regression analysis program outlined in the G.E. Mark III Foreground User's Guide, Dec. 1973, was used to develop this equation.

TABLE 5.6 LIMESTONE SCREENING TEST DATA SUMMARY

Actual Operating Conditions

Run No.	Limestone/SO_2 Stoichiometry	2nd Stage Slurry Rate GPM	SO_2 Removal Efficiency DuPont Analyzer	% Limestone Utilization
38	0.80	2280	73.46	91.79
39	1.53	2250	92.46	60.34
40	1.55	1910	90.02	58.18
41	1.42	2660	88.73	62.32
42	1.08	1890	67.74	62.41
43	1.41	2780	93.22	66.21
44	1.19	1960	85.18	71.74
45	1.30	2780	88.73	68.10
46	1.14	2050	75.07	66.06
47	0.86	2400	75.49	87.92
48	0.94	2280	81.55	86.52
49	1.19	2470	74.82	66.81
50	0.63	1875	48.38	77.38
51	0.96	2680	77.39	80.76
52	0.72	2000	51.55	71.93
53	1.19	2720	78.74	66.02
54	0.94	1750	63.41	67.16
55	1.39	2660	80.96	58.44
56	0.59	1930	42.26	71.20
57	0.94	2250	80.33	85.14
58	1.01	2280	82.60	81.42

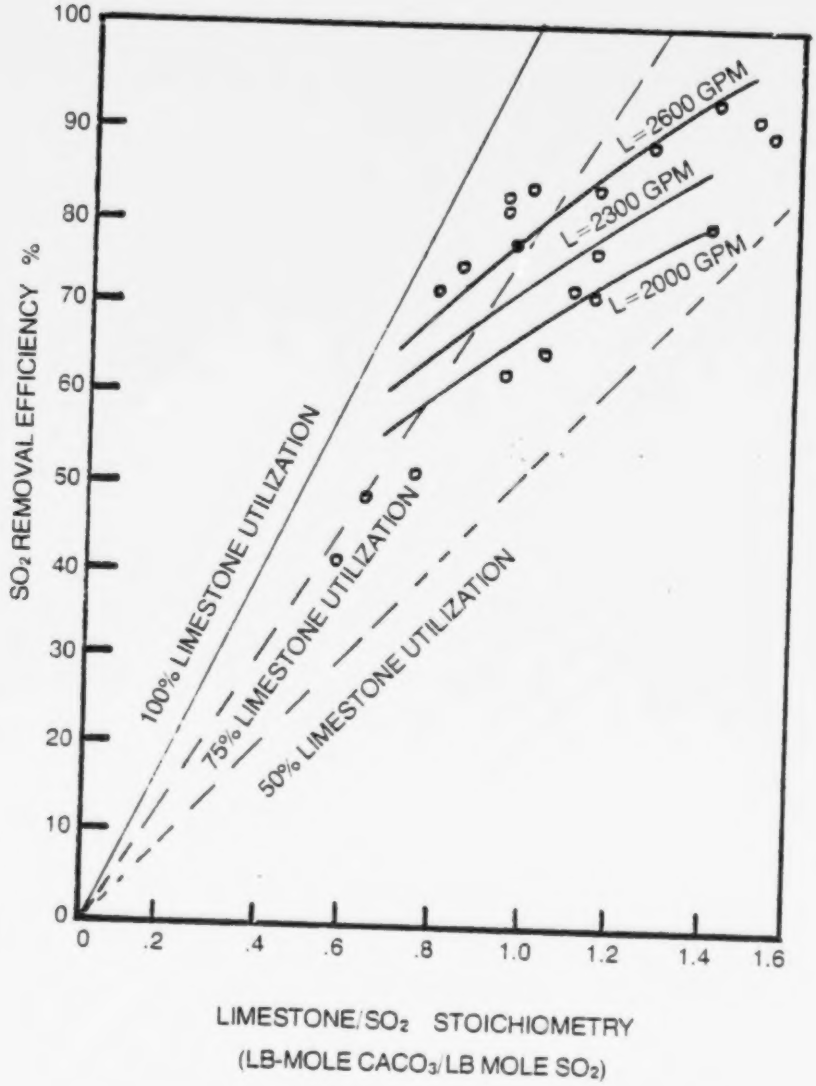

FIGURE 5-4: SO_2 removal efficiency as a function of limestone/SO_2 stoichiometry and slurry pumping rate.

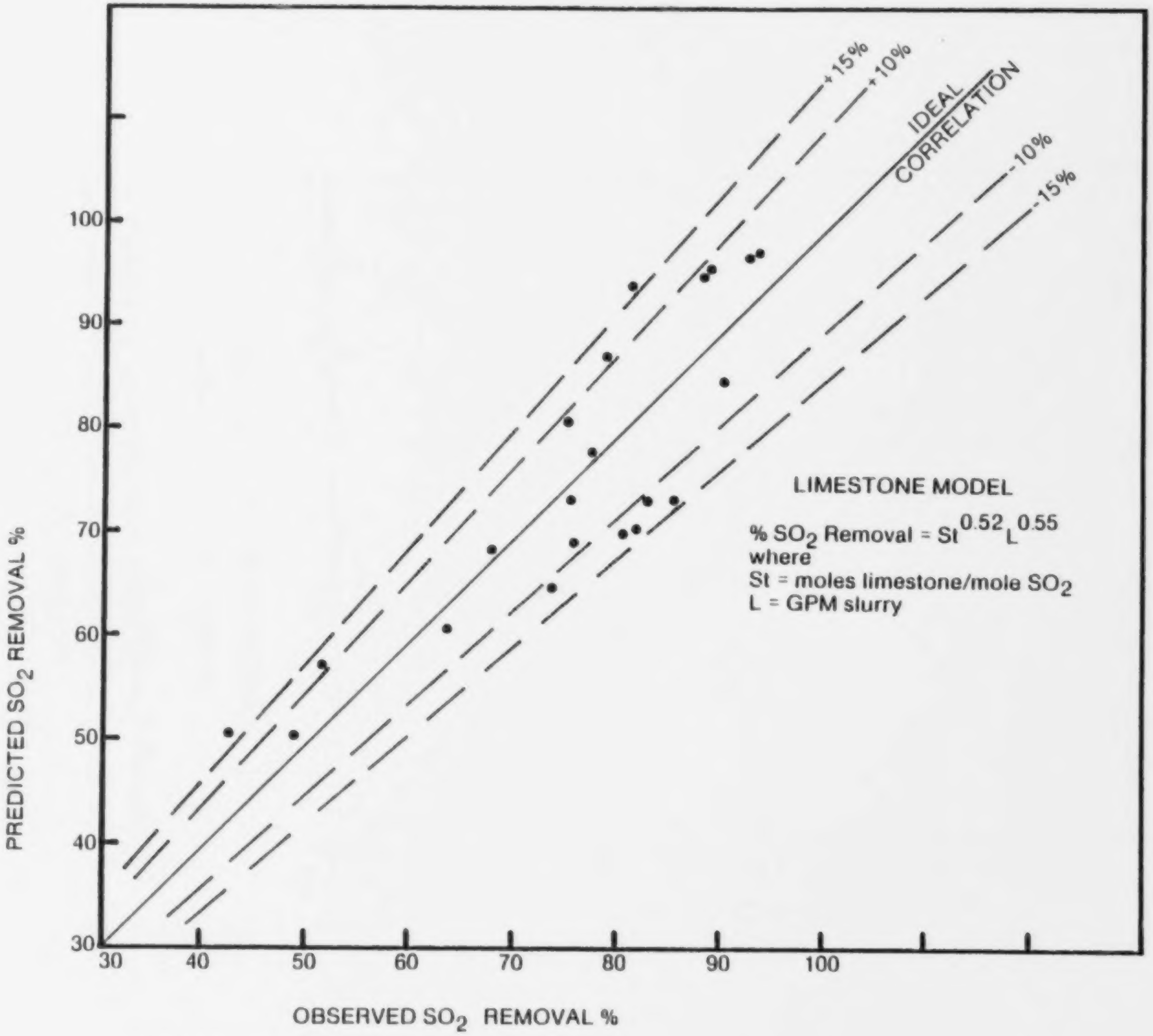

FIGURE: 5-5: A comparison of predicted and observed SO_2 removal efficiencies for limestone.

efficiency perfectly, all of the data points would fall on the Ideal Correlation line. Since there are inherent errors in the measurements of approximately 15%,[4] the model, i.e. Equation (5.1) predicts SO_2 removal efficiency within the range of accuracy expected.

SO_2 removal efficiency and limestone utilization were found to improve with increased second stage slurry pumping rates. Figure 5-4 shows the positive effect on SO_2 removal and limestone utilization of increasing the slurry rate from 2000 to 2600 gpm.

Figure 5-4 also indicates that limestone utilization is about 75% to 90% at lower SO_2 removal levels but decreases significantly above 80% SO_2 removal. The scatter experienced in the runs at 75-80% SO_2 removal is within the uncertainty limits of the data. Limitations on the scope of this test program precluded running verification tests to investigate this further.

Limestone Tests and Stoichiometry

The limestone variable screening test series was a duplication of the tests performed with lime. Minor adjustments in some variables were made to avoid system limit problems and to set stoichiometric ratios at levels suitable for limestone.

Reagent utilization with lime was very often nearly 100%. This resulted in a very small in-process lime inventory and large changes in effective stoichiometry could be made by merely adjusting the lime feed rate. Limestone utilization, however, ranged from 60 to 90% and resulted in a relatively large reagent inventory.

Since the system was being tested in a transient condition, as described in Section 3 Test Procedures, and the effective stoichiometry is more a function of the reagent inventory than the reagent feed rate, it was virtually impossible to obtain the desired levels of limestone/SO_2 stoichiometry. However, stoichiometric ratios from 0.59 to 1.55 were investigated during these tests. The analysis of this data incorporated a two step process. In the first step, a linear regression analysis was performed to approximate the effect of limestone/SO_2 stoichiometry on SO_2 removal efficiency. The remaining variations in SO_2 removal efficiency were analyzed in the same manner as the lime tests to determine the significance, if any, of the other controlled variables relative to SO_2 removal.

Conclusions

Limestone/SO_2 stoichiometry and second stage slurry pumping rate are the significant variables controlling SO_2 removal efficiency.

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(4) See footnote 2, Section 4.

A considerable excess of limestone is needed to absorb SO_2, especially at high SO_2 removal levels.

Limestone can be used to meet the requirements for SO_2 removal at RAFB and other similar coal-fired installations.

LIME VS. LIMESTONE

Both lime and limestone scrubbing reagents have been demonstrated to be very effective in controlling the SO_2 emissions from the boilers at RAFB. Lime is capable of removal efficiencies in excess of 98% with reagent utilizations approaching 100%. Limestone can remove as much as 93% of the inlet SO_2. However, limestone utilization drops below 75% at SO_2 removal efficiencies above approximately 80%.

Reagent Economics

At RAFB, limestone is more economical to use than lime despite the fact that more than twice as much limestone is needed to attain the same SO_2 emission rate. The chemical equations illustrating lime and limestone stoichiometry and weight utilization are:

Lime absorption of SO_2

$$CaO + H_2O = Ca(OH)_2 \qquad (5.2)$$

1 g-mole CaO = 56g.

$$Ca(OH)_2 + SO_2 = CaSO_3 + H_2O \qquad (5.3)$$

1 g-mole SO_2 = 64g.

Limestone absorption of SO_2

$$CaCO_3 + SO_2 = CaSO_3 \qquad (5.4)$$

1 g-mole $CaCO_3$ = 100 g.

1 g-mole SO_2 = 64 g.

Therefore, to absorb one gram-mole of SO_2 (64 grams), 56 g. of lime or 100 g. of limestone are required if a stoichiometric equivalent of either reagent is used. Since lime was completely utilized compared to an average of 75% for limestone, more representative numbers are 62 grams[5] of lime used versus 133

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(5) These values include allowances for typical impurities found in these reagents.

grams of limestone. The price of limestone delivered to the RAFB during 1977 was $12.72/ton compared to $40.35 for lime. This large price differential gives limestone the economic advantage, for every $100 spent for limestone $141.20 must be spent for an equivalent amount of lime.

In addition limestone is not hygroscopic and need not be slaked, thus eliminating the need for a complex slaking device. Finally, limestone is far less likely to cause injuries to operating or maintenance personnel since it does not exhibit the potentially damaging caustic properties inherent in lime.

Limestone and Oxidation

A large increase in the ratio of sulfate to sulfite in the scrubber slurry was observed when the shift from lime to limestone was made during the test program. Table 5.7 shows an average calcium sulfate ($CaSO_4 \cdot 2H_2O$) and calcium sulfite ($CaSO_3 \cdot \frac{1}{2}H_2O$) content of 36% and 57%, respectively, when lime was being used. The limestone slurry is more fully oxidized and contained 75% sulfate and less than 1% sulfite. The comparison of average lime and limestone slurry analyses during similar boiler load periods listed in Table 5.7 indicates that this oxidation trend is probably attributable to the effect of the reagent used on the system's average pH as discussed below since all other operating conditions were essentially the same.

Dissolver Slurry pH

As illustrated in Figure 5-6, dissolver slurry pH measurements taken during the limestone tests were significantly different from those taken during the lime tests. Although the limestone/SO_2 stoichiometry was varied over a range of 0.59 to 1.53, the accompanying slurry pH variation was only 4.9 to 6.2. In comparison, the lime slurry pH was much more sensitive to stoichiometric changes. The dissolver slurry pH varied from 4.3 to 9.6 at stoichiometric levels from 0.36 to 1.08.

In the lime test series, the relationship between the dissolver slurry pH and stoichiometry was used as a means to estimate stoichiometry during the test program.

TABLE 5.7 LIME AND LIMESTONE SLURRY ANALYSES

Slurry Solids	Lime Slurry May 1976 wt %	Limestone Slurry May 1977 wt %
$CaSO_4 \cdot 2H_2O$	33.4	77.5
$CaSO_3 \cdot \frac{1}{2}H_2O$	54.5	1.0
$CaCO_3$	3.7	17.3
$MgCO_3$	-	0.8
Acid Insoluables	4.6	3.4
TOTAL	96.2	100.0

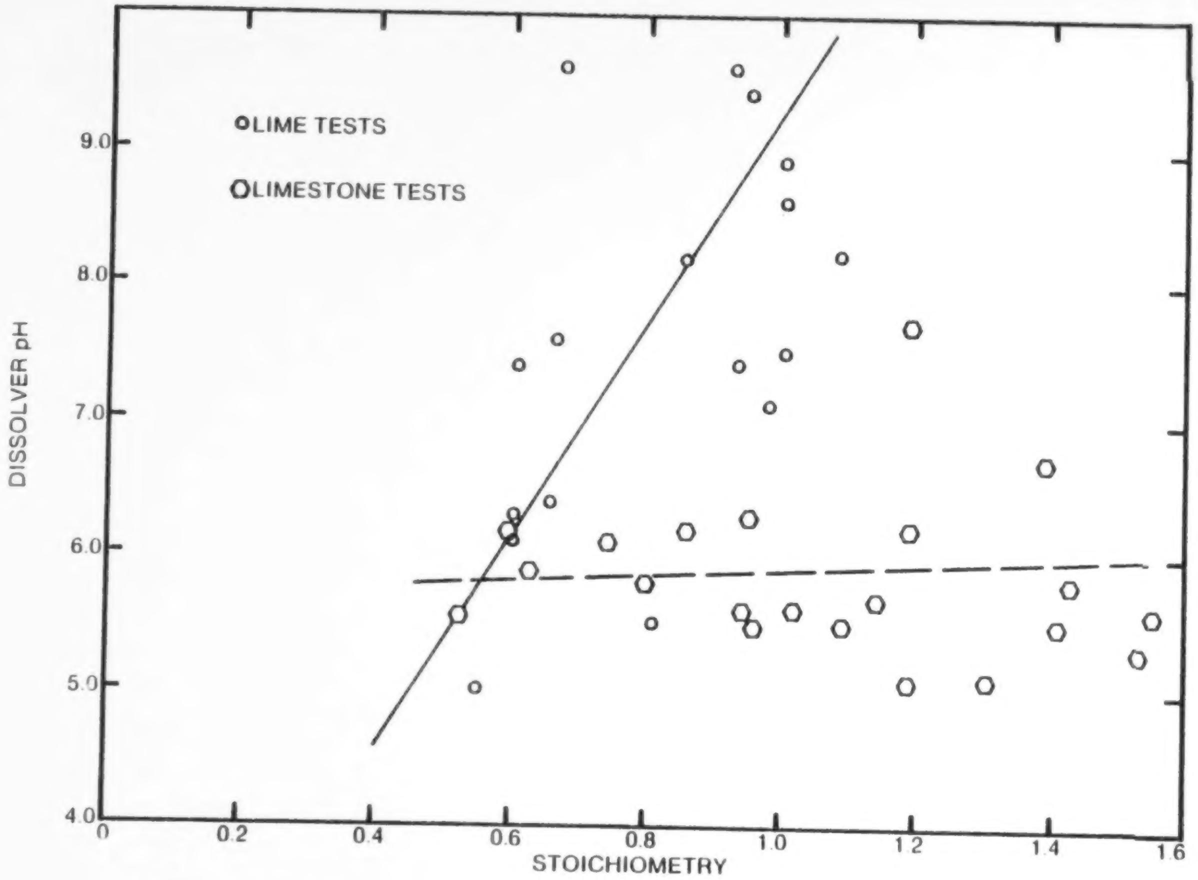

FIGURE 5-6: The effect of lime and limestone stoichiometry on dissolver pH.

CONCLUSIONS

- Lime is a more efficient reagent than limestone for SO_2 removal in the R-C/Bahco scrubber.

- Limestone is a more economical reagent than lime because of the large reagent price differential.

- Limestone scrubber solids contain substantially higher sulfate levels than those from lime scrubbing. This is due to lower system pH levels normally associated with limestone.

Note: See Section 7 page 117 regarding the relation between the use of limestone and scrubber solids sulfate levels.

SECTION 6

PARTICULATE REMOVAL TESTS

INITIAL PARTICULATE REMOVAL TESTS

Initial particulate removal tests on the R-C/Bahco scrubber performed in March, April and May of 1976 revealed the presence of unexpected amounts of particulate in the stack gas. The average particulate emission rate for these tests, listed in Table 6.1, was 0.23 lbs./MM Btu.[1] Overall particulate removal averaged 93 to 94% for these tests.[2] The Ohio emission standards require an overall removal efficiency of about 96% at a particulate inlet loading of 1.5 grains per SCFD to achieve an emission rate of 0.16 lbs./MM Btu.

The R-C/Bahco system at RAFB was designed with extra fan capacity to carry out this test program. This extra capacity was utilized to help reduce particle emissions levels. Venturi pressure drops were increased to nearly double the design value of 7 in. w.c. to accomplish this end. Data from these preliminary tests are plotted in Figure 6-1 to show the effect of the combined pressure drop of the two venturis in the R-C/Bahco scrubber on particulate emissions. Below approximately 18 in. H_2O total pressure drop, particulate emissions increased rapidly.

Since outlet particulate loadings were higher than anticipated, tests were run and the results analyzed to determine the cause. Particulate size distribution data from several sources, listed in Table 6.2, were collected and analyzed.

The particle size data shown in Figure 6-2 was derived from Pratt-Daniel data supplied for the original installation of the generators. This particle size distribution is typical for stoker fired coal burning equipment operating without any particulate controls. This information was used to estimate the particle size distribution and loading for the R-C/Bahco scrubber at RAFB.

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(1) Additional particulate emission data is listed in Appendix H.
(2) Including particulate removed by the mechanical collectors.

TABLE 6.1 PARTICULATE EMISSION RATES

Date	Particle Loading, gr/SCF		Gas Flow Rate, SCFM*	Boiler Firing Rate, MM Btu/hr.	Total Pressure Drop, in H_2O	Particulate Emissions Rate, LBS/MM Btu
	Inlet	Outlet				
3/18/76	-	0.178	42,800	128.2	15	0.51
3/30/76	-	0.075	37,500	132.6	19	0.18
3/30/76	-	0.059	37,500	132.6	19	0.14
4/8/76	-	0.036	50,500	115.2**	27	0.14
4/29/76	-	0.072	45,500	94.8	15	0.30
4/30/76	-	0.038	47,200	94.8	18	0.16
5/20/76	-	0.024	54,200	57.7	23	0.19

* Flue gas flow rates were based on fan motor current readings and fan pressure differentials

** The total firing rate was 132.3 MM Btu/hr.; however, 13% of the flue gas was bypassed.

TABLE 6.2 INLET PARTICLE SIZE DISTRIBUTIONS

Flue Gas Stream Location	Source	Remarks
Boiler Outlet	Pratt-Daniel	Boilers Manufacturer's Data
Scrubber Inlet	Design Model	Calculated For Two Mechanical Collectors in Series
Scrubber Inlet	R-C Particulate Tests May 1976	Samples were collected in Andersen Impactors

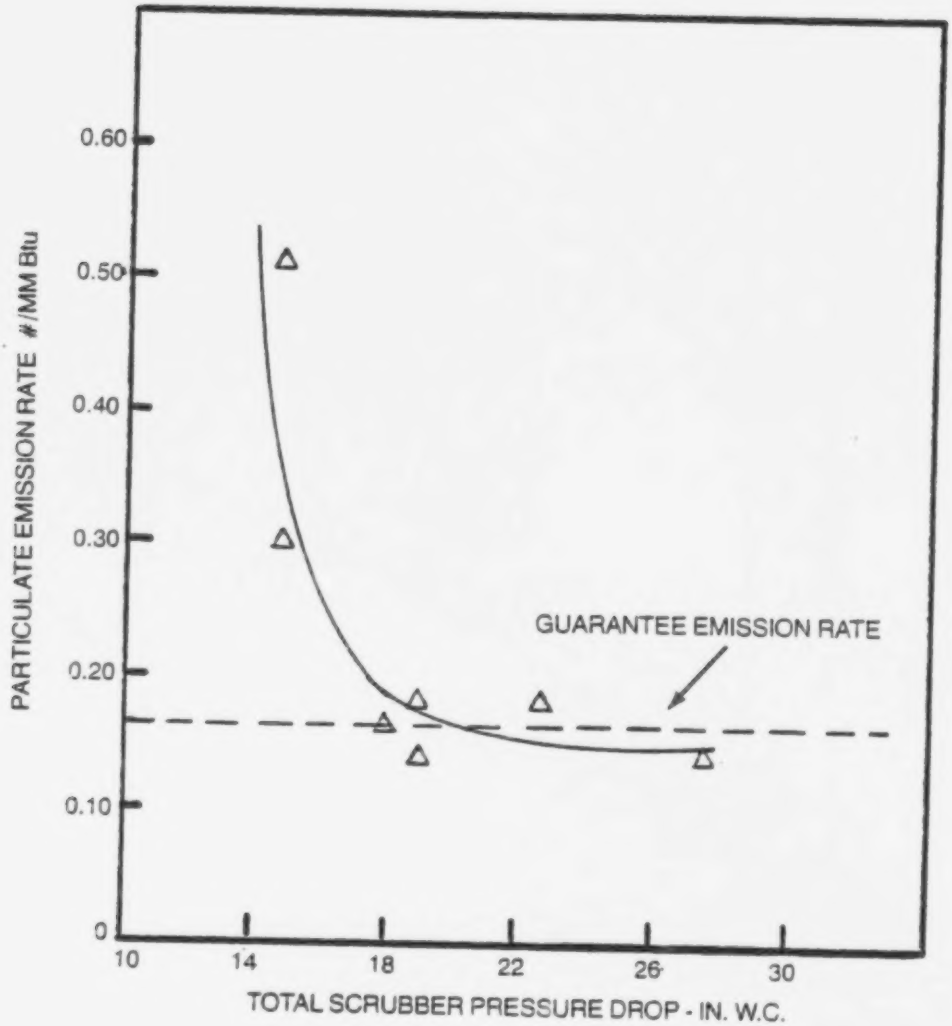

FIGURE 6-1: The effect of scrubber pressure drop on particulate emission rates.

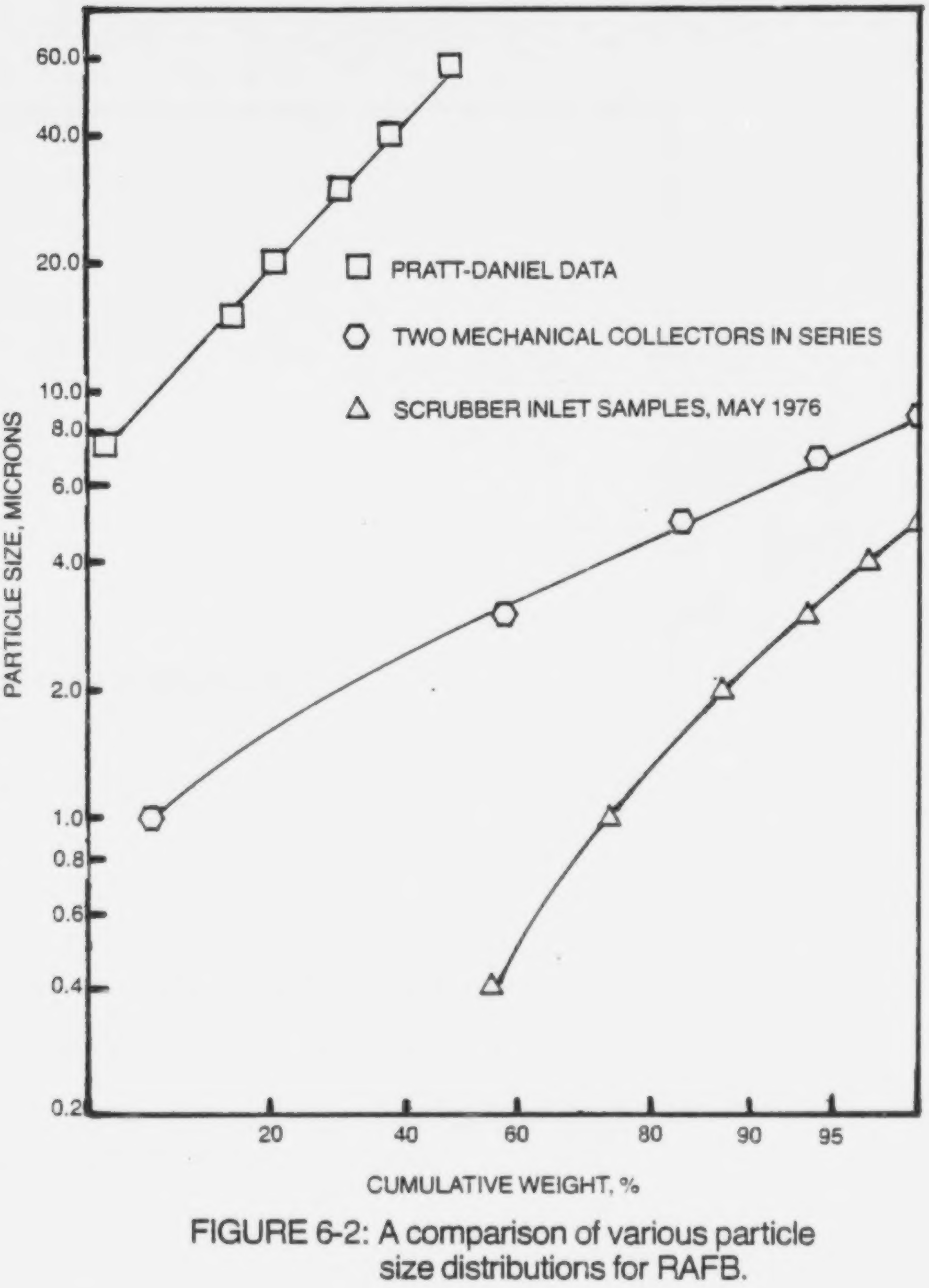

FIGURE 6-2: A comparison of various particle size distributions for RAFB.

The amount of soot present in the flue gas at RAFB is substantially higher than normal for stoker fired generators of this type. The USAF has undertaken an extensive program to upgrade the heat plant at RAFB. Data obtained during this test program contributed substantially to information used by the USAF to plan this upgrading program.

The following items have been undertaken or completed:

- Installation of a new 60 Btu/hr. generator to replace two old units.
- Replacement of hot water distribution piping.
- Installation of flue gas oxygen monitoring equipment.
- Repair of firing air distribution equipment and fire box pressure controls in the generators.
- Rebuilding mechanical collectors and I.D. fans on the generators.
- Replacement of burned out ledge plates, which regulate combustion air flow around the grates, and repair of the traveling grates.

FRACTIONAL EFFICIENCY TESTS

Tests were run at RAFB over a wide range of operating conditions to determine fractional particulate removal efficiencies. The effect of gas flow rates, and other process variables were determined for a number of particulate size fractions. Andersen Impactors were used during these tests. Table 6.3 summarizes the results of these tests. Major system variables and the particle diameters at which 50% and 90% collection efficiencies were obtained are also listed.

The particle diameter at which 90% collection efficiency was obtained varied from 0.67 microns to 1.24 microns. Increasing the total scrubber pressure drop decreased the particle diameter at which 90% collection was observed, i.e. collection efficiency increased. Figure 6-3 presents the effect of the combined pressure drop of the first and second stages of the scrubber on the particle size at which 90% collection was achieved. Particulate collection efficiency in this range of sizes appears to be unaffected by the gas flow rate.

For 50% particulate collection efficiency, the diameter ranged from 0.42 to 0.72 microns and was related to total scrubber pressure drop and gas rate. Figure 6.4 shows that increasing the pressure drop and increasing the gas rate acted to increase particulate collection as evidenced by the decrease in the diameter observed for 50% collection efficiency. Pressure drops beyond about 16 in. W.C. had no effect on improving particulate collection efficiency.

TABLE 6.3 FRACTIONAL EFFICIENCY TEST RESULTS

Test No.	Inlet Gas Flow SCFMx10^{-3}	1st Stage ΔP, in W.C.	2nd Stage ΔP, in W.C.	Flue Gas Temp, °F	1st Stage Liquid Pickup GPM	2nd Stage Liquid Pickup GPM	50% Part. Diameter Microns	90% Part. Diameter Microns
1	40.5	7.0	9.0	440	1200	600	0.66	1.00
2R	35.3	4.5	4.8	428	165	90	0.67	0.98
4	53.1	11.0	13.0	480	1400	840	0.43	0.72
10	41.5	9.5	8.0	473	1050	540	0.58	0.92
11	42.8	9.5	8.5	478	1100	600	0.72	0.97
12R	53.7	5.3	5.3	353	255	105	0.70	1.24
15	30.3	12.7	6.6	492	780	450	0.72	1.06
18R	33.2	4.5	13.0	435	220	810	0.67	0.96
2	32.9	12.0	9.0	478	1350	810	0.55	0.78
7	34.2	9.5	10.7	485	400	480	0.59	0.82
12	55.3	8.0	8.0	468	1050	600	0.44	0.67
18	33.7 - 41.8	13.0	12.0	448	1050	1140	0.66	0.94

Note: Gas flow rates were based on booster fan motor current readings and differential pressures.

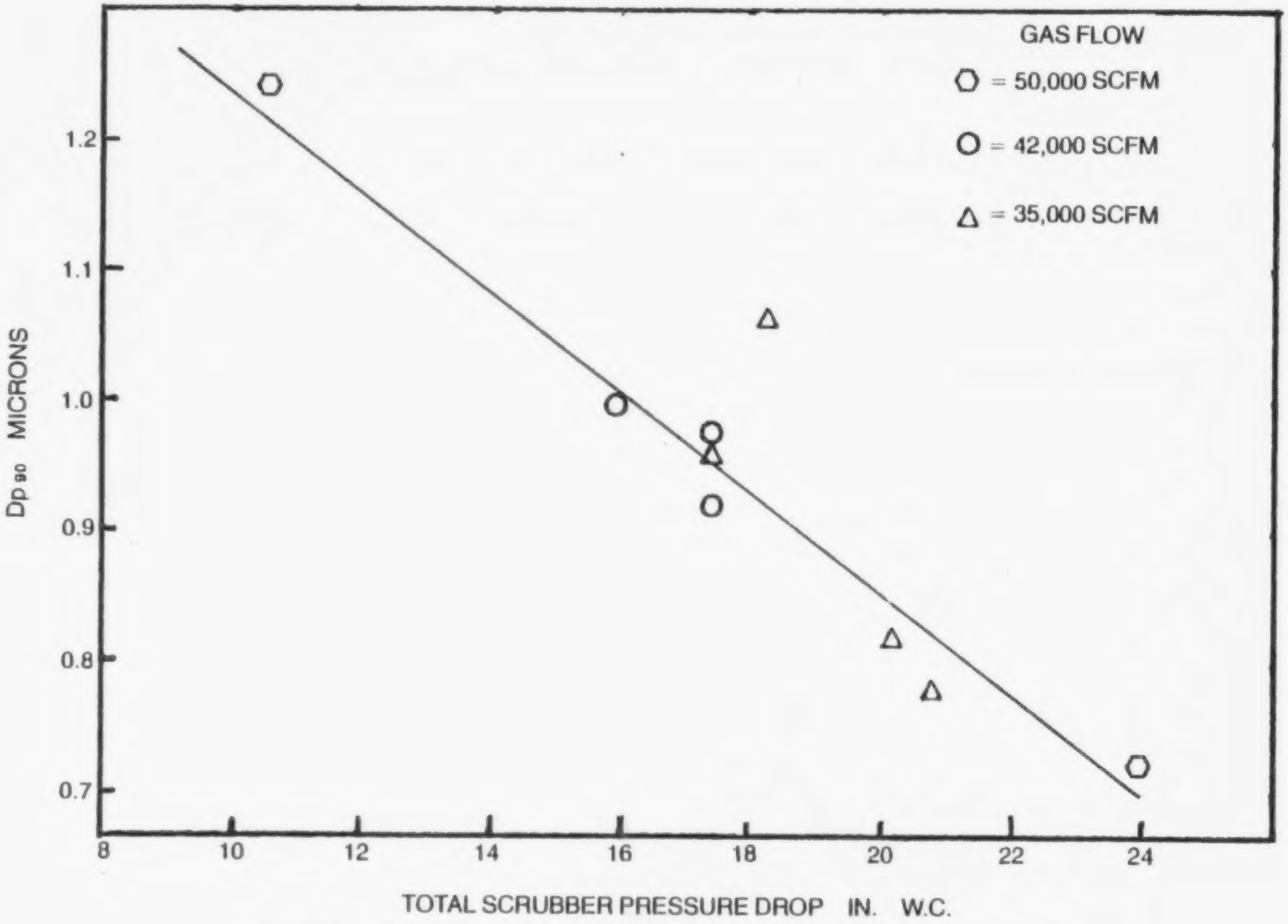

FIGURE 6-3: The effect of total scrubber pressure drop on the cut off diameter for 90% collection efficiency.

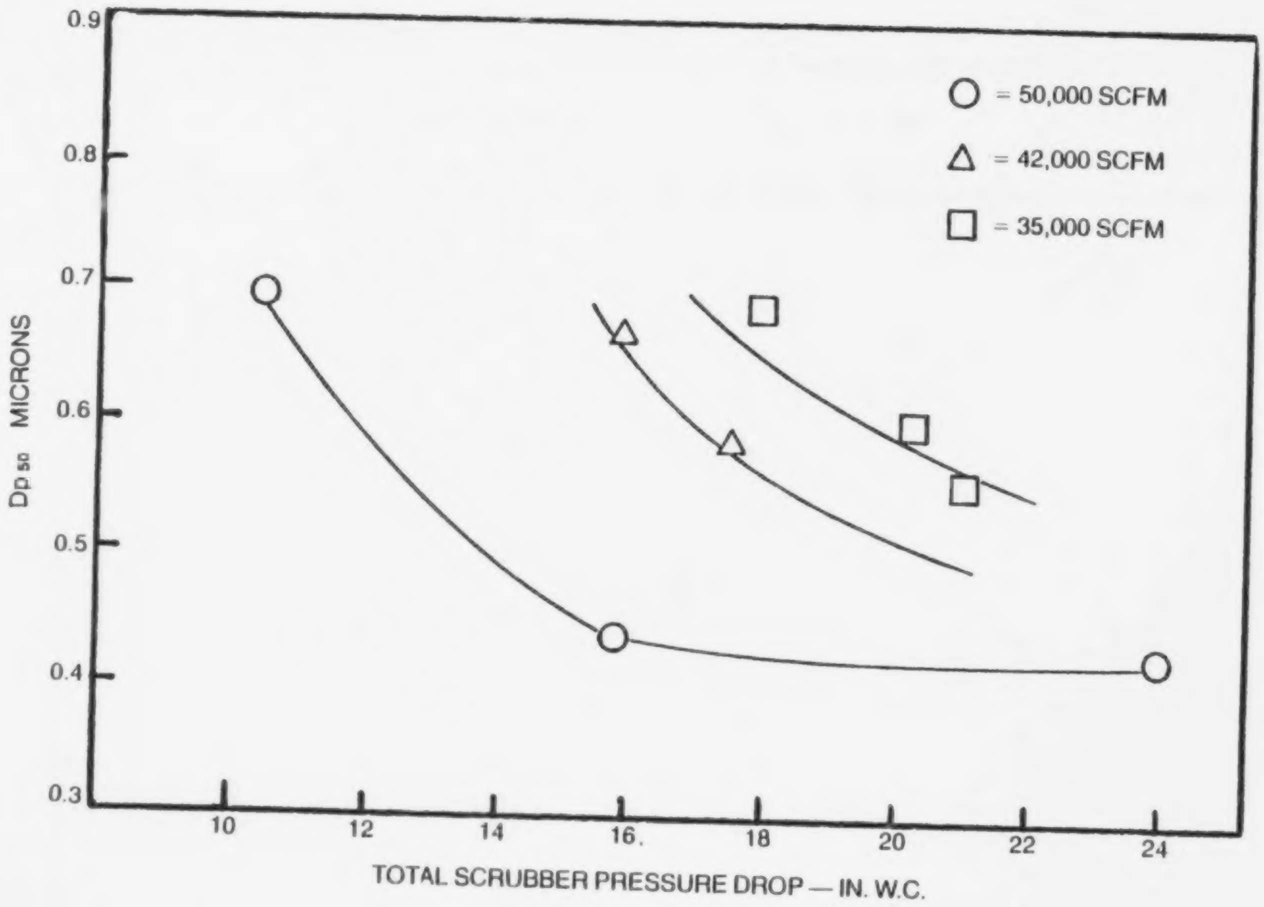

FIGURE 6-4: The effect of total scrubber pressure drop and gas rate on the cut off diameter for 50% collection efficiency.

Flue gas from each generator passes through two mechanical collectors before entering the scrubber. The first mechanical collector is mounted on each hot water generator upstream from its I.D. Fan. The other is located upstream from the booster fan in the main flue.

The second particle size distribution illustrated in Figure 6-2 was derived from the Pratt-Daniel data by calculating the particulate collected from the original distribution for each of the mechanical collectors.[3] Average flue gas rates resulting in a pressure drop of 2 in. w.c. for each collector and a fly ash density of 2.0 gm/cm^3 were selected for this calculation.

Based on a 1.5 grains per SCFD loading from the generators, a grain loading of 0.1 grains per SCFD entering the scrubber was estimated from the above analysis.

The particulate tests conducted in May, 1976[4], to gain insight into the particulate emissions problem, revealed the presence of considerably more fine particulate than anticipated. The data from these tests is plotted as the third distribution.[4]

Figure 6.2 shows that 70 to 80 wt. % of the particulate entering the scrubber is less than 1 micron as opposed to an expected 8 to 10 wt.%. Samples of this particulate appear very sooty on visual inspection. In addition, the material has a low specific gravity ($\approx$ 1.3) and a high loss on ignition ($\approx$ 35%).

A typical grain loading for the flue gas at RAFB is 1.0 grain per SCFD. The first mechanical collector should have reduced the grain loading to 0.14 grains per SCFD and the second to 0.07 grains per SCFD before the particulate matter entered the scrubber. The scrubber must remove half of the remaining particulate in order to meet code requirements. Based on size distribution tests and chemical analyses, it is estimated that 10-20% or 0.1-0.2 grains per SCFD of the total particulate matter is soot.

A soot level of 0.1 grains per SCFD, if uncollected, corresponds to an emission rate of about 0.5 lbs. particulate/MM Btu. The test results indicate that soot levels well over three times the allowable emission rate of 0.16 lbs./MM Btu were present. Actual removal efficiencies at loadings of approximately 0.15 to 0.25 grains per SCFD were in the 40 to 80% range, resulting in an overall particulate removal efficiency of 93-94%. This data indicates the R-C/ Bahco scrubber performed very well on material for which it was not designed to collect.

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(3) See Appendix H for particulate removal efficiency data for the mechanical collectors.

(4) The individual test data is also located in Appendix H.

As indicated in Figure 6-5, collection efficiency for particles above 3 microns is essentially complete. In addition, Figure 6-5 shows the particle size range at which 50, 90 and 98% particulate collection was observed during this portion of the test program.

PARTICULATE COLLECTION AT SYSTEM LIMITS

While analyzing the test results it became apparent that a few tests were conducted outside the scrubber operating limits described in Table 4.1 above for gas flow rate and venturi pressure drops.

Two phenomena which resulted in decreased particulate collection were observed. The results of these tests, runs 2R, 12R and 7, are presented in Figure 6-6 and Figure 6-7. Tests 2R and 12R exhibited a phenomenon called slurry droplet "entrainment" and test 7 illustrates what is termed gas "bypassing". Pertinent gas flow and pressure drop data for these tests is listed in Table 6.3.

Entrainment

The inlet and outlet particle size distribution curves in Figure 6-6 reveal that particles as small as about 2 to 3 microns are removed effectively by the scrubber. In run 2R, however, for particles above 3 microns, the apparent collection efficiency dropped off drastically. Collection decreased to the point where very little collection occurred in the 9 to 12 micron range, instead of the normal outlet level indicating essentially 100% removal. Run 2R was conducted at a second stage venturi pressure drop of 4.8 in. w.c. and a gas rate of 35,300 SCFM. The most likely explanation for this behavior is the following: at these operating conditions fine slurry droplets are generated in the second stage venturi which are not removed in the second stage mist eliminator. This phenomenon was observed at both high and low gas flow rates, but occurred only when operating at very low pressure venturi drops, i.e., 4 to 5 in. W.C.

There are further indications which point to slurry droplet carryover at these operating conditions. The amount of carryover observed in Test 2R is high enough to raise the emission of particles in the 9-12 micron range almost as high as they were in the inlet gas. Pressure drops in Test 12R were similar to those in Run 2R (4.8 in. w.c. vs. 5.3 in. w.c.), but the scrubber gas rate was higher, i.e. 53,700 SCFM. In Run 12R, some carryover occurred but not nearly as much as experienced at the lower gas rate. This difference may be due to the ability of the second stage mist eliminator to collect droplets of slurry in the 10 micron range more effectively at the higher gas rate experienced in Run 12R.

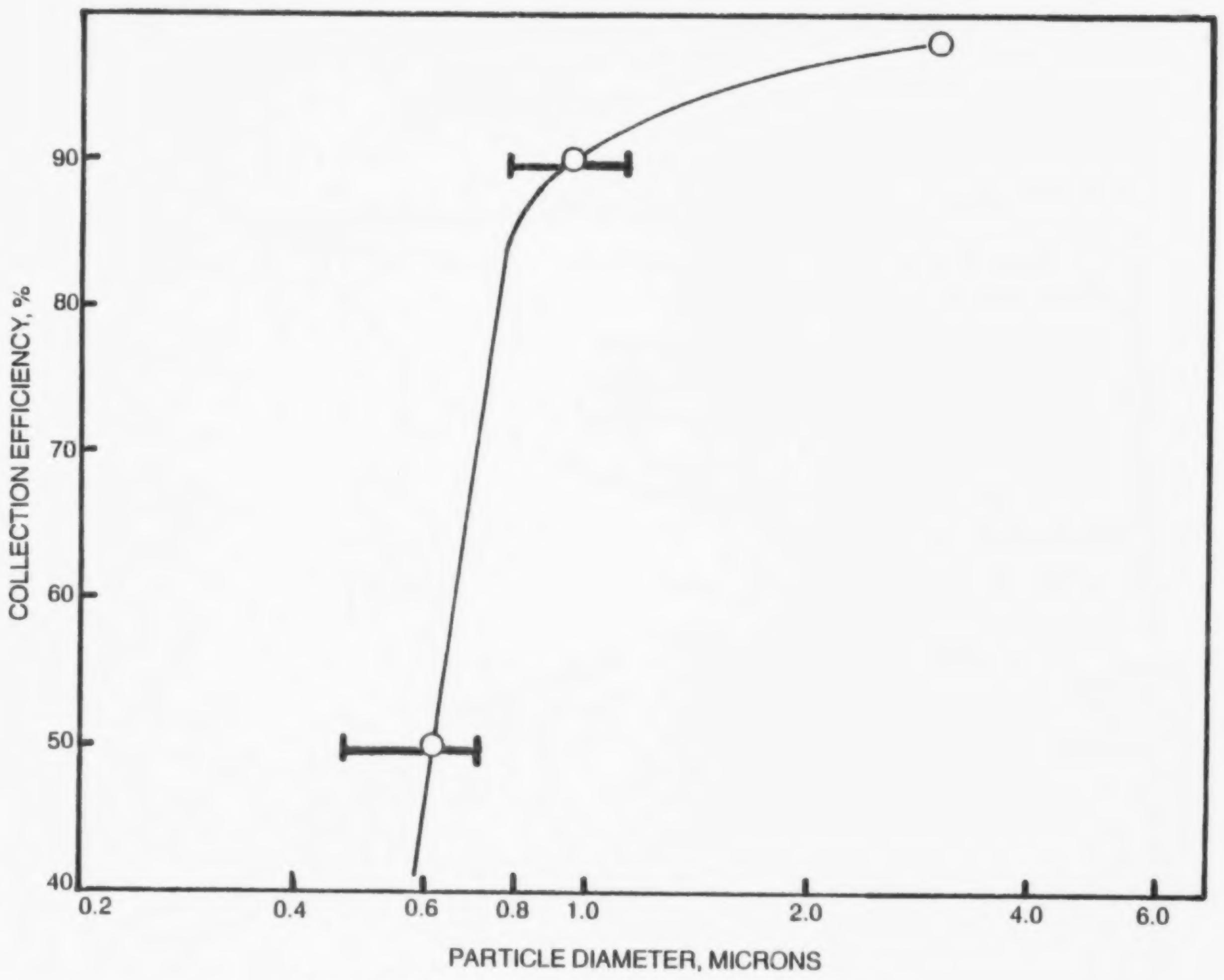

FIGURE 6-5: Particulate collection efficiency as related to particle size at RAFB.

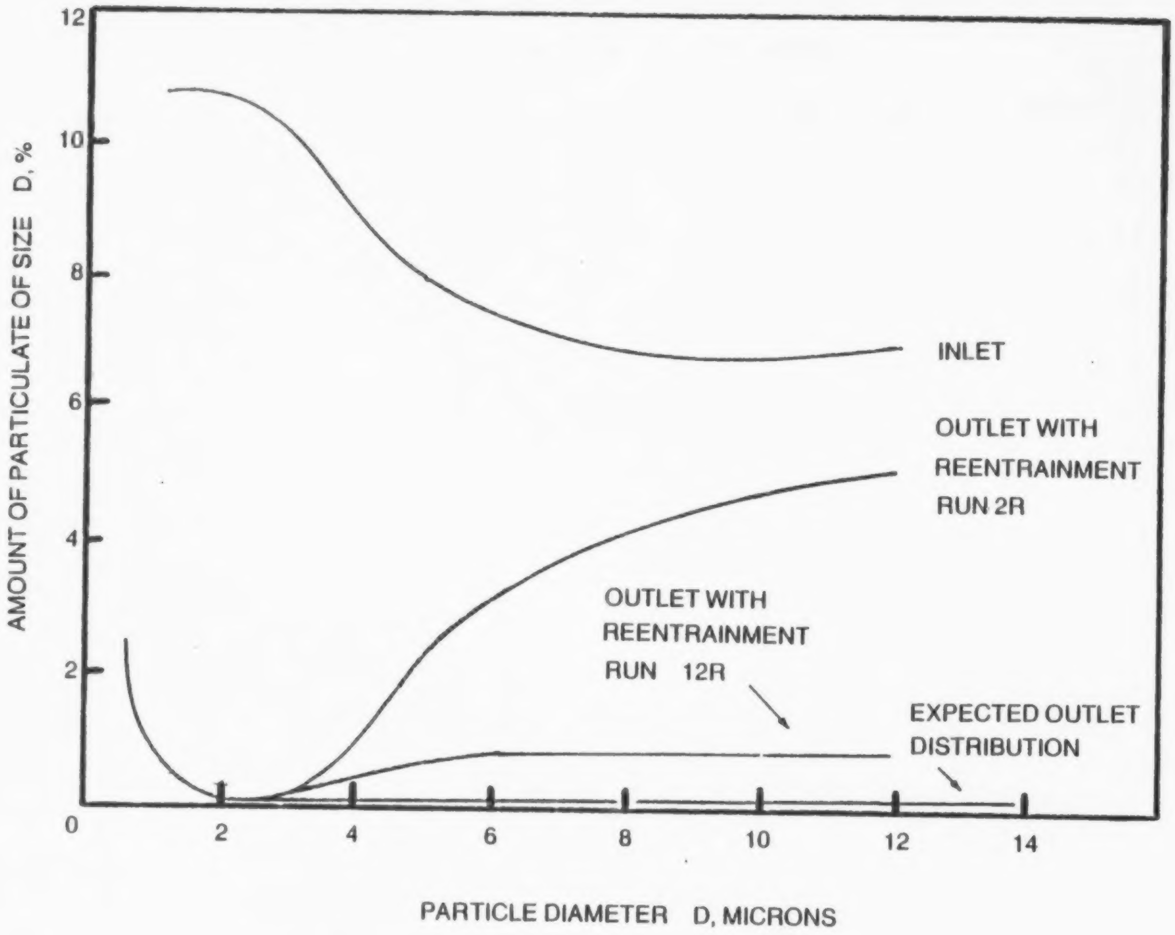

FIGURE 6-6: Examples of reentrainment from the R-C/Bahco scrubber at RAFB.

Bypassing

The second phenomenon observed during Run 7 is called bypassing, illustrated in Figure 6-7. Particulate collection is uniformly poor over the entire range of particle sizes observed. It is as if part of the gas stream was bypassing around the venturis. This condition is characterized by pulsating flow through the system and occurs when relatively high pressure drop in either stage is coupled with low slurry flow to the scrubber. When the system is operating in this manner, the current drawn by the fan motor varies over a range of 5 amps at a frequency near one cycle per second. In addition, liquid pickup in the venturis is less than expected for the observed combination of gas flow and pressure drop. It appears that the flue gas picks up more slurry than is being pumped to the scrubber thereby dropping the slurry level and back pressure, allowing a surge of flue gas through the venturi. As the slurry begins to catch up, the pressure drop increases and the flue gas flow decreases. However, since the average slurry rate is too low, the process is repeated until conditions are changed to eliminate the imbalance between slurry flow and venturi liquid pickup.

Table 6.4 presents the liquid pickup rates measured on the first and second venturi stages of the R-C/Bahco scrubber as a function of pressure drop, gas rate and slurry circulation rate. These results were obtained over a pressure drop/stage range up to about 15 in. H_2O and gas flow rates from 33,000 SCFM to 55,000 SCFM. Figure 6-8 illustrates the normal amounts of liquid pickup in each venturi and the results from Run 7R where bypassing occurred. For the first stage at 9.5 in. H_2O pressure drop, a slurry pickup rate of only 400 GPM was obtained in Run 7R compared to the expected rate of 1000 - 1400 GPM. In the second stage at 11.2 in. H_2O pressure drop, a 500 GPM pickup rate was observed compared to an expected 900-1,200 GPM.

It is important to note that this condition only occurs when the slurry flow to the scrubber is intentionally reduced to less than 50% of the normal flow rate of 2600 GPM and the venturi pressure drops are increased to more than 50% above normal operating levels of 6-8 in. w.c.

PARTICULATE PERFORMANCE MODEL

The R-C/Bahco scrubber treats flue gas using two venturis in series. The most commonly used collection mechanism for describing particulate removal in the size range observed at RAFB is inertial impaction.[5] This is the prevailing mechanism for collection of particles above 0.5 microns in diameter.

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(5) W. Strauss, Industrial Gas Cleaning, Pg. 215, Pergamon Press 1966.

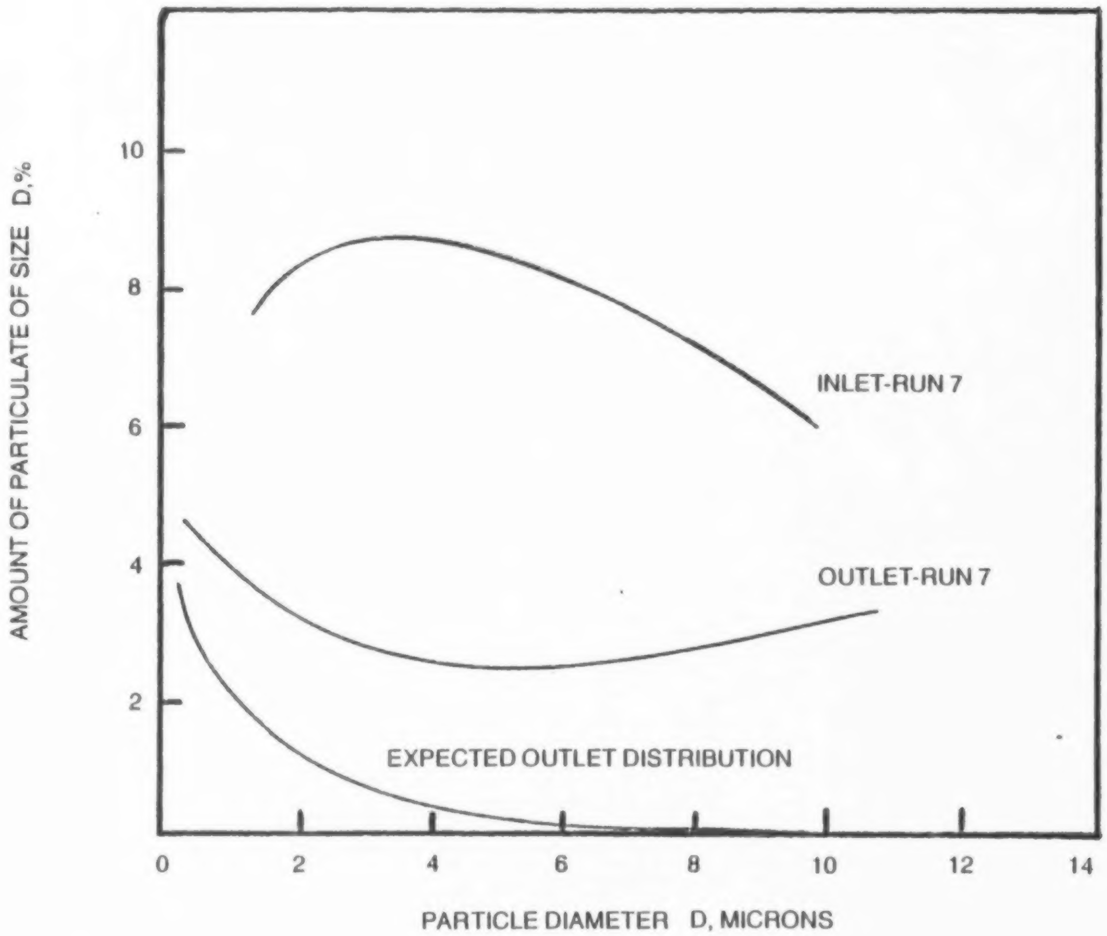

FIGURE 6-7: An example of bypassing from the R-C Bahco scrubber at RAFB.

TABLE 6.4 VENTURI LIQUID PICKUP RATES

Test No.	Inlet Gas Flow SCFM	Total Pressure Drop, in. w.c.		Second Stage Slurry Pumping Rate, GPM	Liquid Pickup, GPM	
		First Stage	Second Stage		1st Stage	2nd Stage
1	40,500	7.0	9.0	2780	1200	600
2R	35,300	4.5	4.8	3000	165	90
4	53,100	11.0	13.0	3100	1400	840
7	34,200	9.5	10.7	1750	400	480
10	41,500	9.5	8.0	2230	1050	540
11	42,800	9.5	8.5	2700	1100	600
12R	53,700	5.3	5.3	3000	255	105
15	30,300	12.7	6.6	2400	780	450
18R	33,200	4.5	13.0	3000	220	810
2	32,900	12.0	9.0	3000	1350	810
12	55,300	8.0	8.0	2800	1050	600
18	33,700-41,800	13.0	12.0	2400	1050	1140

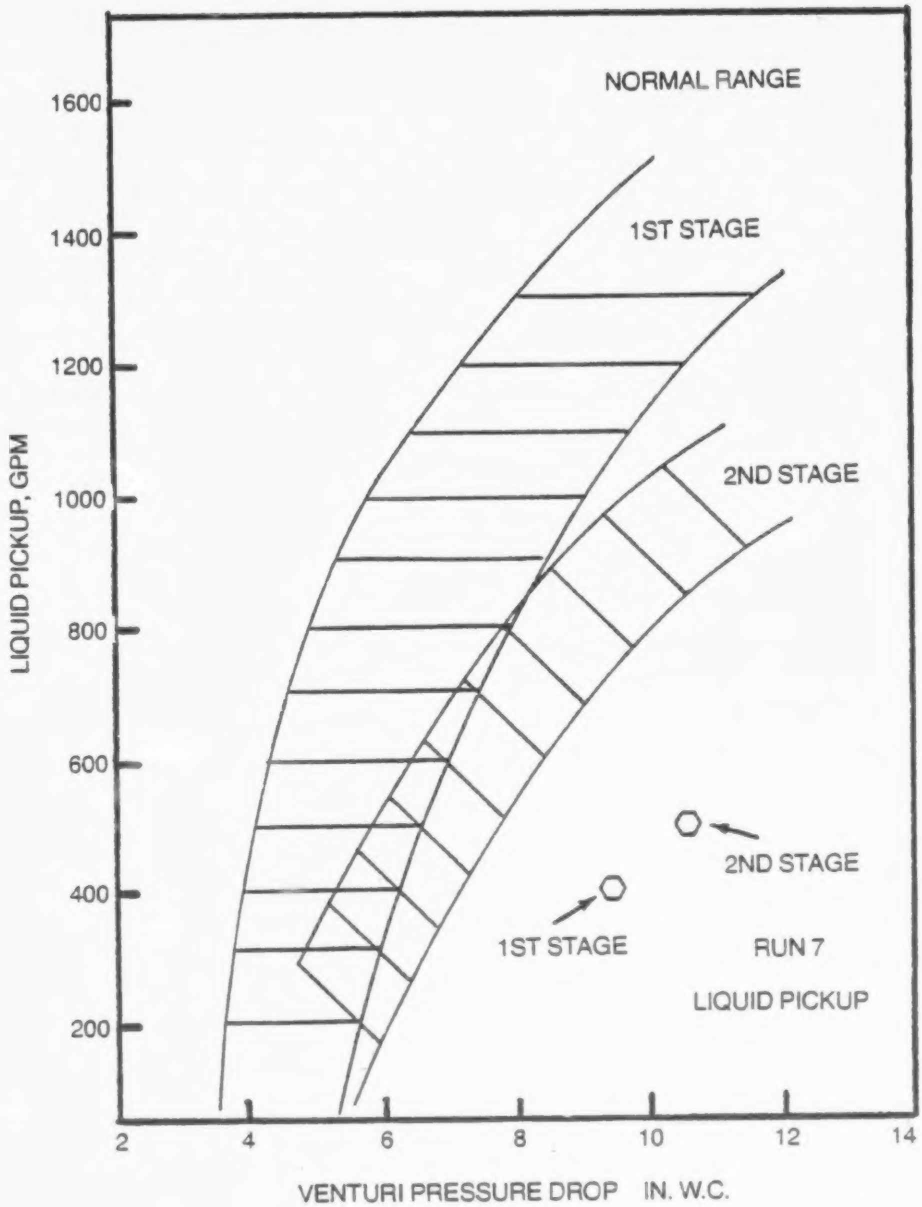

FIGURE 6-8: The effect of venturi pressure drop on liquid pickup.

Inertial impaction occurs when the inertia of a particle causes it to continue to move toward and collide with the collecting medium, slurry droplets, as the gas stream changes direction in flowing around the collecting medium. According to inertial impaction theory, collection efficiency can be related to scrubber variables and particle size by using the following relationship:

$$P = 1 - \eta \approx \text{exp. } \{a(L/G) \quad \Psi\} \qquad (6.1)$$

where P = penetration or the fraction of particulate not collected

η = the fraction of particulate collected

a = an empirical constant

L/G = stage liquid slurry/gas ratio, GPM/1000 CFM

Ψ = inertial impaction parameter defined below:

$$\Psi = \frac{C' \, (p_p - p_g) \, d_p{}^2 v_o}{18 \, \mu \, D} \qquad (6.2)$$

In equation (6.2), C' = Cunningham correction factor, dimensionless

p_p = Particle density, gm/cm^3

p_g = Gas Density, gm/cm^3

d_p = Particle diameter, cm

v_o = Gas velocity, cm/sec

μ = Gas viscosity, Pas.

D = Droplet diameter, cm

For the purposes of this analysis several simplifications in the inertial impaction model, i.e. Equation (6.1), were made. First, the collector droplet size, D, was assumed to be inversely proportional to gas velocity at average temperature conditions in the venturi(6):

$$D \approx \frac{1}{V_o} = \frac{492}{G \, T_{av}} \qquad (6.3)$$

where G = Gas flow rate, SCFM

---

(6) This is based on a simplification of the equation developed by Nukiyama and Takasawa, Trans. Soc. Mech. Eng. (Japan), 4, (14) 86, (1938).

T_{av} = Average temperature, ^{o}R

The average gas temperature was estimated using a root-mean-square absolute temperature:

$$T_{av} = (T_{Gas\ inlet} + 460)(T_{slurry} + 460) \qquad (6.4)$$

This particular mean was chosen to emphasize the effects of gas velocity before gas cooling occurred in the scrubber. The slurry was used to represent the outlet gas temperature and was in the temperature range of 125°F for all runs. Since all the other factors in Equation (6.1) are constant for a given particle size and temperature, the inertial impaction parameter can be approximated by:

$$\psi = a_1\ d_p\ G\ T_{av} \qquad (6.5)$$

By combining Equations (6.1) and (6.5), the particulate penetration for the first scrubber stage can be determined.

$$P_{1st\ stage} \approx \exp.\ \{a_1\ (L_1G_1)\ d_p\ G\ T_{av}\} \qquad (6.6)$$

or more simply,

$$P_{1st\ stage} \approx \exp\ \{a_1\ L_1\ d_p\ T_{av}\} \qquad (6.7)$$

The penetration expression for the second or upper stage is analogous to the first stage but simpler in form since the inlet gas temperature in the second stage is essentially the same as the outlet or slurry temperature. The average temperature in Equation (6.5) can be incorporated into the constant term:

$$a_2 = a\ T_{av} \qquad (6.8)$$

Thus, the second stage penetration can be expressed as,

$$P_{2nd\ stage} \approx \exp\ \{a_2\ L_2\ d_p\} \qquad (6.9)$$

For the R-C/Bahco scrubber with two stages in series, P_o, the overall particulate penetration is the product of the penetration for each stage,

$$P_o = P_{1st}\ P_{2nd}d = (\exp\ \{a_1\ L_1\ d_p\ T_{av}\})(\exp\ \{a_2 L_2 d_p\} \quad (6.10)$$

Analysis of the Test Results

A regression analysis of the fractional efficiency test results was performed using the penetration model developed in Equation (6.10). The penetration model coefficients a_1 and a_2 for the first and second stages are given in Table 6.5. Average particle size and collection efficiency test results were used for the regression analysis.

The results predicted from the Equation (6.10) and the values determined in the test program are compared in Figure 6.9. Figure 6.10 compares the observed and predicted collection efficiency for the particle size ranges selected for analysis.

An analysis of the results in Table 6.5 indicates that collection of particles above and below one micron occur in different stages of the scrubber. This conclusion is supported in part by the relatively small changes which occurred in correlation coefficients when single stage models were used.

It appears that particles larger than 1 micron are collected in the first stage of the scrubber. For example, Table 6.6 shows that in the 2.0-5.0 micron range the predicted collection efficiency changes from 99.8% to 98.4% when the second stage is eliminated from the model. As a further indication of the minimal significance of the second stage on particulate collection above 1 micron, one should note the effect of eliminating the second stage on the first stage model coefficient and the correlation coefficient. The first stage coefficient changes somewhat from -0.232×10^{-5} to -0.172×10^{-5} but more significantly the correlation coefficient decreases by only 1% from 0.97 to 0.96.

A similar situation occurs for the second stage for fine particulate collection. For 0.3 - 0.5 micron particles, the second stage is the primary collector. Typical values for collection efficiency are 50.9% for a one stage model and 43.8% for a two stage model. Thus, each scrubber stage functions to collect a different portion of the total particulate distribution.

The comparison presented in Figure 6-9 and 6-10 indicates that there is some variability between the observed and predicted particulate penetration.

Two factors which contributed to scatter in the test results and complicated particulate testing were:

TABLE 6.5 PENETRATION MODEL COEFFICIENTS (1)

Particle Size Range, microns (2)	No. of Stages In Model	First Stage Model Coefficient (3) a_1	Second Stage Model Coefficient a_2	Correlation Coefficient
0.3 - 0.5 (0.4)	2	0.376×10^{-6}	-0.269×10^{-2}	0.91
0.3 - 0.5 (0.4)	1	----	-0.221×10^{-2}	0.91
0.5 - 1.0 (0.7)	2	0.519×10^{-6}	-0.229×10^{-2}	0.83
0.5 - 1.0 (0.7)	1	-----	-0.185×10^{-2}	0.83
1.0 - 2.0 (1.4)	2	-0.210×10^{-5}	-0.478×10^{-3}	0.94
1.0 - 2.0 (1.4)	1	-0.251×10^{-5}	-----	0.94
2.0 - 5.0 (3.2)	2	-0.232×10^{-5}	0.710×10^{-3}(2)	0.97
2.0 - 5.0 (3.2)	1	-0.172×10^{-5}	-----	0.96

---

(1) The regression analyses in which these coefficients were determined are located in Appendix H.

(2) Average particle size used to determine penetration model coefficients shown in parentheses.

(3) These positive correlation coefficients are strictly empirical since they must posses negative values to have physical significance

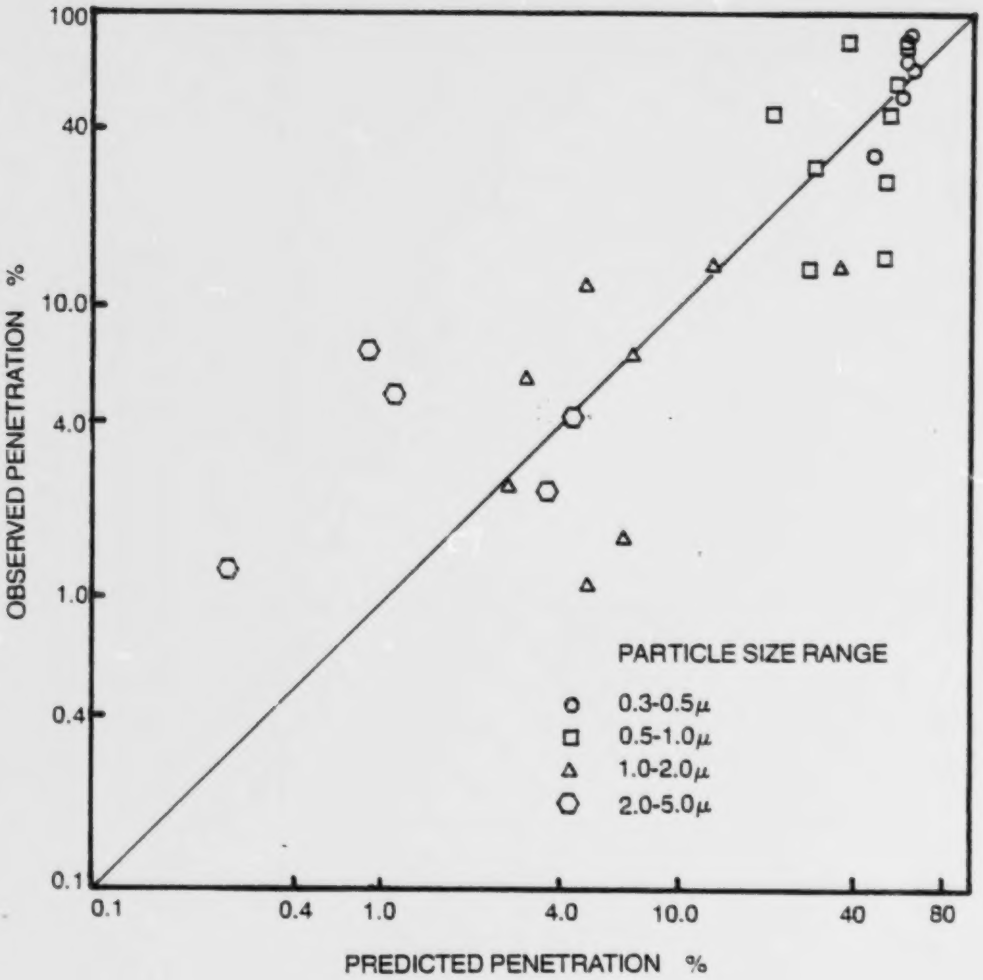

FIGURE 6-9: A comparison of observed and predicted particulate penetration.

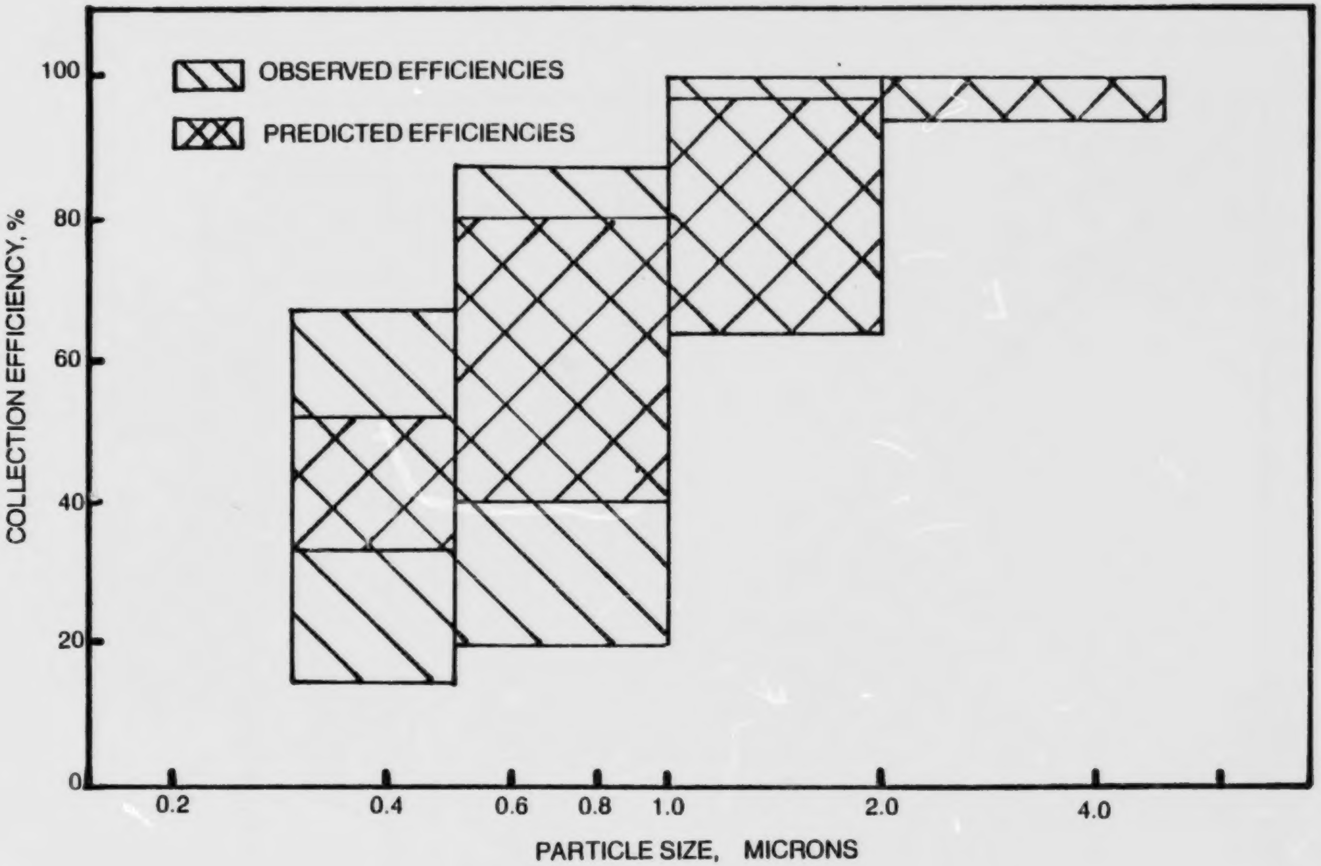

FIGURE 6-10: A comparison of observed and predicted particulate collection efficiencies for the R-C/Bahco scrubber at RAFB.

1. The variability of boiler operation which resulted in fluctuating flue gas rates and compositions to the scrubber during the tests.

2. Changes in the particulate characteristics when fine soot was generated along with fly ash.

However, the results indicate that the simplified inertial impaction model used in this analysis does adequately represent the observed particulate collection.

TABLE 6.6 A COMPARISON OF ONE AND TWO STAGE MODELS

Particle Size Range, Microns	One Stage Model* Collection Efficiency %	Two Stage Model* Collection Efficiency %
0.3 - 0.5 (0.4)	50.7	43.8
0.5 - 1.0 (0.7)	64.5	63.5
1.0 - 2.0 (1.4)	93.0	92.6
2.0 - 5.0 (3.2)	98.4	99.8

*These values were calculated using the following values for system variables:

L_1 = 1100 GPM

L_2 = 800 GPM

$T_{av} = 688\ ^{o}R$ ($T_{Gas\ inlet} = 350^{o}F$)

Since large sized particles are collected efficiently in the first stage, very few large particles remain to be collected in the second stage. For certain applications, where high combustion efficiency in the boiler can be maintained, it may not be necessary to use two stages for particulate collection since the generation of fine particulate would be minimal.In addition to collecting large particles, the first stage may also help condition fine particulate in the flue gas to enhance collection in the second stage. Gas cooling and humidification processes occurring in the first scrubber stage may condition the fine particles via nucleation and growth mechanisms to make them more susceptable to capture in the second stage.

CONCLUSIONS

- The particulate removal efficiency of the R-C/Bahco scrubber is comparable to that of low energy venturi scrubbers for particles larger than 1 micron and appears to be better for particles smaller than 1 micron.
- In an R-C/Bahco scrubber the second stage is the primary collector for fine particles.
- Slurry carryover and gas bypassing limit particulate collection in an R-C/Bahco scrubber when operating beyond the systems gas handling and venturi pressure drop limits.
- Particulate emissions from stoker fired coal burning equipment can be reduced to acceptable levels if excessive soot formation does not occur.

SECTION 7

SCRUBBER SLUDGE CHARACTERIZATION TESTS

A series of scrubber sludge characterization tests were carried out in the R-C laboratories to accomplish the following objectives:

- Determine scrubber sludge dewatering characteristics
- Evaluate transportability of dewatered sludge
- Determine physical/structural properties of dewatered sludge
- Measure sludge leachate for environmental acceptability.

The laboratory tests outlined below were performed on samples collected at RAFB during the lime and limestone testing described in Section 5 of this report.

SLURRY DEWATERING

- Settling
- Centrifugation
- Vacuum Filtration

TRANSPORTABILITY

- Truckability
- Angle of Repose
- Slump
- Slide

PHYSICAL/STRUCTURAL

- California Bearing Ratio
- Unconfined Compressive Strength

LEACHATE

- Trace Metal Analysis
- Total Dissolved Solids, Sulfate and Chloride
- Chemical Oxygen Demand

SLURRY DEWATERING

Settling Tests

Six settling tests were run on lime and limestone slurry samples to determine rates and final sludge solids. A commonly used flocculant, Betz 1100, was tested at 2 and 5 ppm to study its effectiveness. Slurries containing 16 to 17 wt. % solids were used for settling tests. These tests were performed in 2,000 ml graduated cylinders.

Limestone slurries which contained substantial amounts of gypsum settled much more rapidly than lime slurries as indicated in Figure 7-1. The flocculant had no effect on lime slurry settling rates but improved settling substantially on the gypsum limestone slurries. As Table 7.1 shows, the settled sludge concentration was not affected by the addition of flocculant for either type of slurry. However, limestone slurries with their high gypsum content produced a settled layer with a higher solids content, 58 wt.% vs. 43-45 wt.% for lime.

Centrifuge Tests

Laboratory tests indicated that centrifugation produces a denser cake from limestone slurries which contained substantial amounts of gypsum than from lime slurries. As Figure 7-2 shows, this effect is more pronounced at higher slurry feed concentrations.

With a 37-38 wt.% solids feed, limestone slurry dewatered to 65-67 wt.% solids while the lime slurry reached only 56-58 wt.%. Centrifugation produced a 50-55% solids concentration for both slurries when the feed concentration was reduced to 20-25 wt.%. Figure 7-2 also reveals that the slurry solids reached nearly maximum compaction within the first five minutes. Continued operation at 800 g's for up to twenty minutes increased solids content by only 2-3 wt%. Lime and limestone centrifuge test results are summarized in Table 7.2.

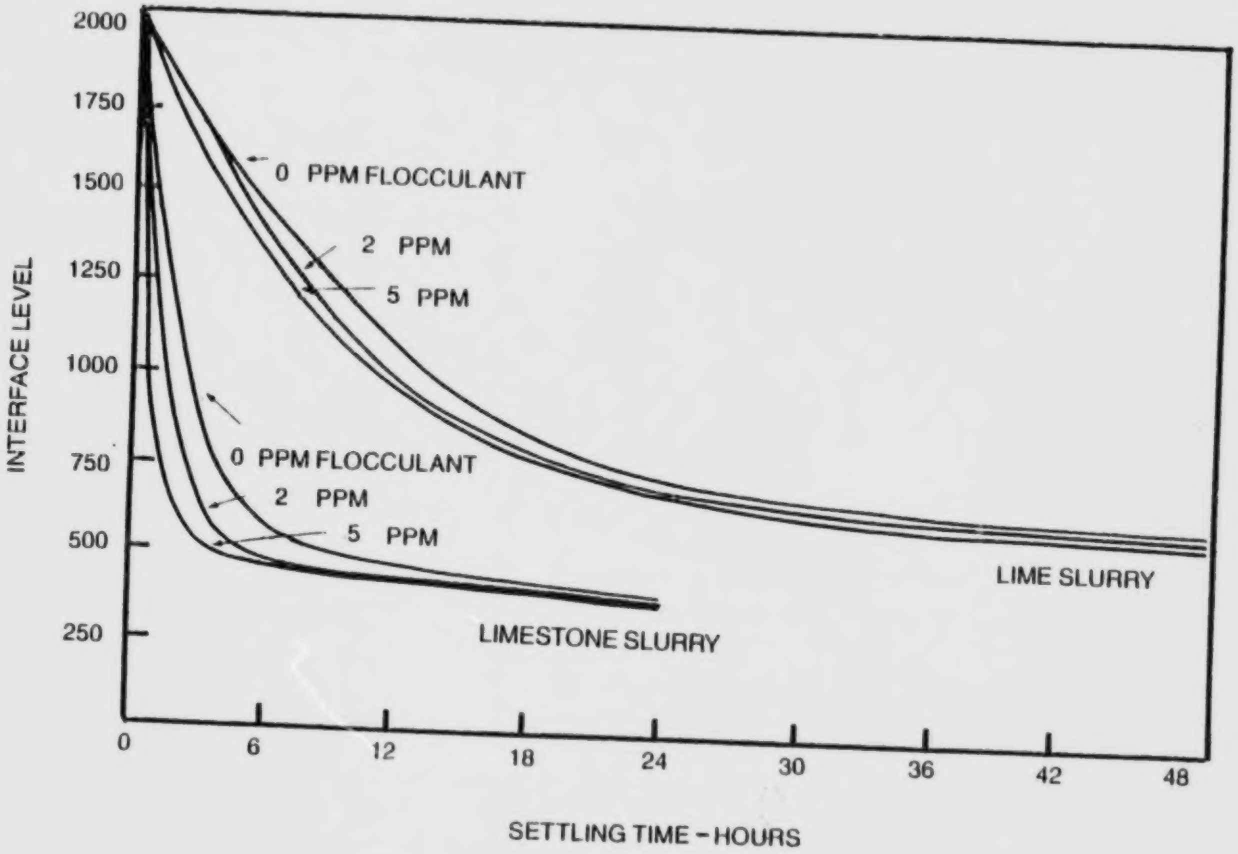

FIGURE 7-1: A comparison of lime and limestone slurry settling rates.

TABLE 7.1 SETTLING TEST RESULTS

Test No.	L_1	L_2	L_3	LS_1	LS_2	LS_3
Scrubber Reagent	Lime	Lime	Lime	Lime-stone	Lime-stone	Lime-stone
Floc Type Added	None	Betz 1100	Betz 1100	None	Betz 1100	Betz 1100
Floc Conc. ppm	0	2	5	0	2	5
Feed Wt.% Solids	16.15	16.15	16.15	16.66	16.66	16.66
Settled Sludge Wt.% Solids	43.31	45.32	44.03	58.35	58.86	57.50
Settling Rate* lbs/ft^2 day	20.1	22.7	22.3	164.3	350.0	578.1

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* at an underflow concentration of 35% solids

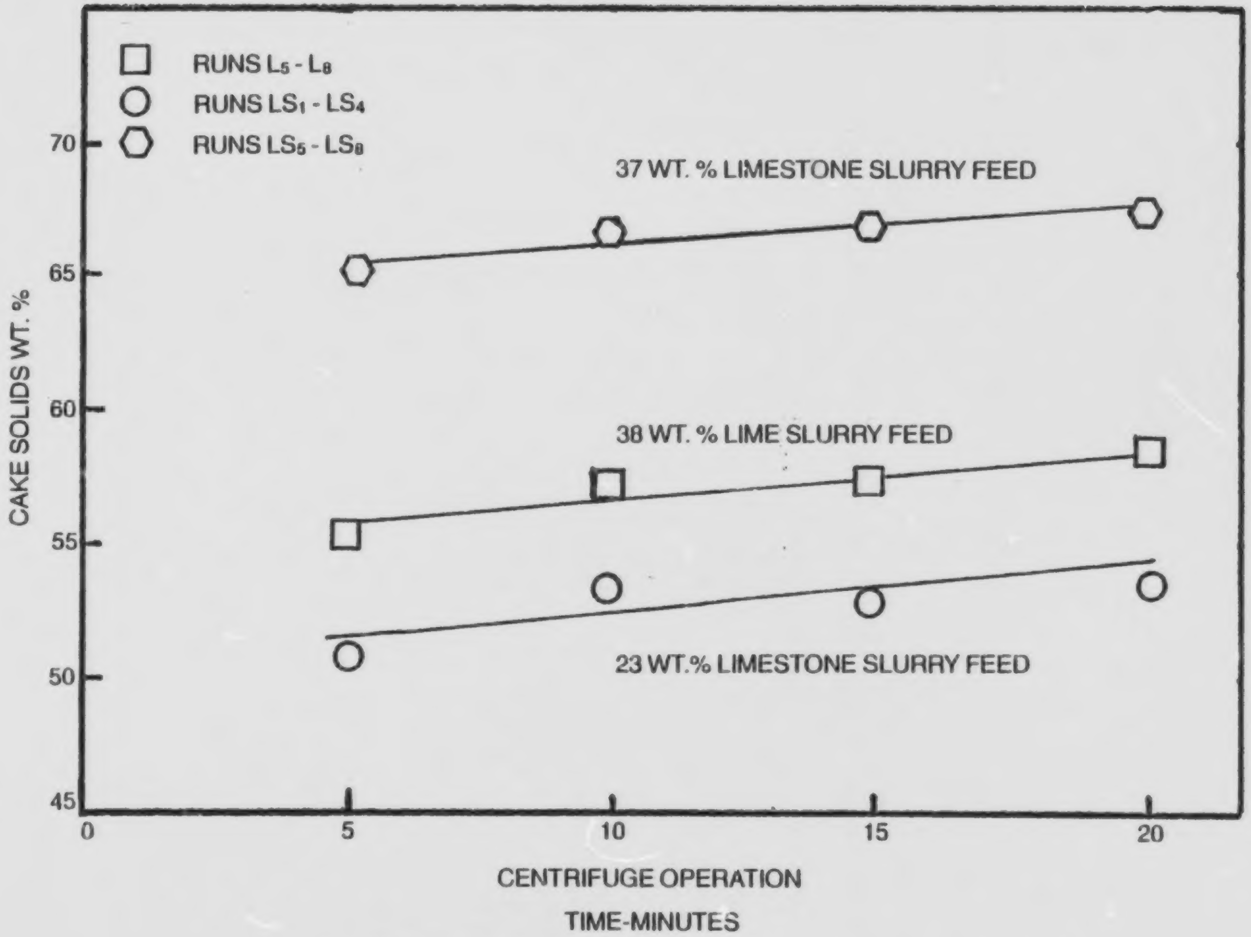

FIGURE 7-2: The effect of operating time and slurry feed concentration on centrifuge cake density.

TABLE 7.2 CENTRIFUGE TEST RESULTS

Run No.	Feed Wt.% Solids	Centrifuge Time (min)	Cake Wt.% Solids
L-1	26.27	5	50.63
L-2	26.27	10	50.16
L-3	26.27	15	52.04
L-4	26.27	20	50.44
L-5	38.35	5	55.66
L-6	38.35	10	56.95
L-7	38.35	15	57.28
L-8	38.35	20	58.68
LS-1	22.92	5	51.04
LS-2	22.92	10	53.19
LS-3	22.92	15	53.56
LS-4	22.92	20	54.31
LS-5	37.40	5	65.18
LS-6	37.40	10	66.44
LS-7	37.40	15	66.82
LS-8	37.40	20	67.41

Filter Leaf Tests

Filter leaf tests show that limestone slurry filtration rates are significantly lower than lime slurry rates. Figure 7-3 and Table 7.3 present filtration rates for the five composite filter leaf tests performed. Filtration rates measured for lime and limestone slurries ranged from 43 to 150 lbs of solids per hour for each square foot of filter cloth. The tests were conducted on a 0.1 ft^2 filter with an 853 Eimco polypropylene filter cloth (59 x 38 thread count).

Figure 7-3 also shows that the filtration rate increases with increasing slurry solids concentration and decreases with increasing form time. As shown in Table 7.3, filtration produced a more concentrated filter cake from limestone slurries (74 wt.%) which contained substantial amounts of gypsum than from lime slurries (58%). Form filter time had no effect on the filter cake solids content for either type of slurry in our tests using a vacuum of 26.0 in. Hg.

Lime vs. Limestone Dewatering

Photomicrographs, Figures 7-4 and 7-5, taken of the slurry samples listed in Table 7.4 show that the lime slurry crystals which were predominately calcium sulfite tend to be small and needlelike, whereas the limestone slurry crystals which were predominately gypsum (calcium sulfate) are larger and more block-like. These large crystals in the limestone slurry promote more rapid dewatering in most instances and result in higher solids concentrations in dewatered products.

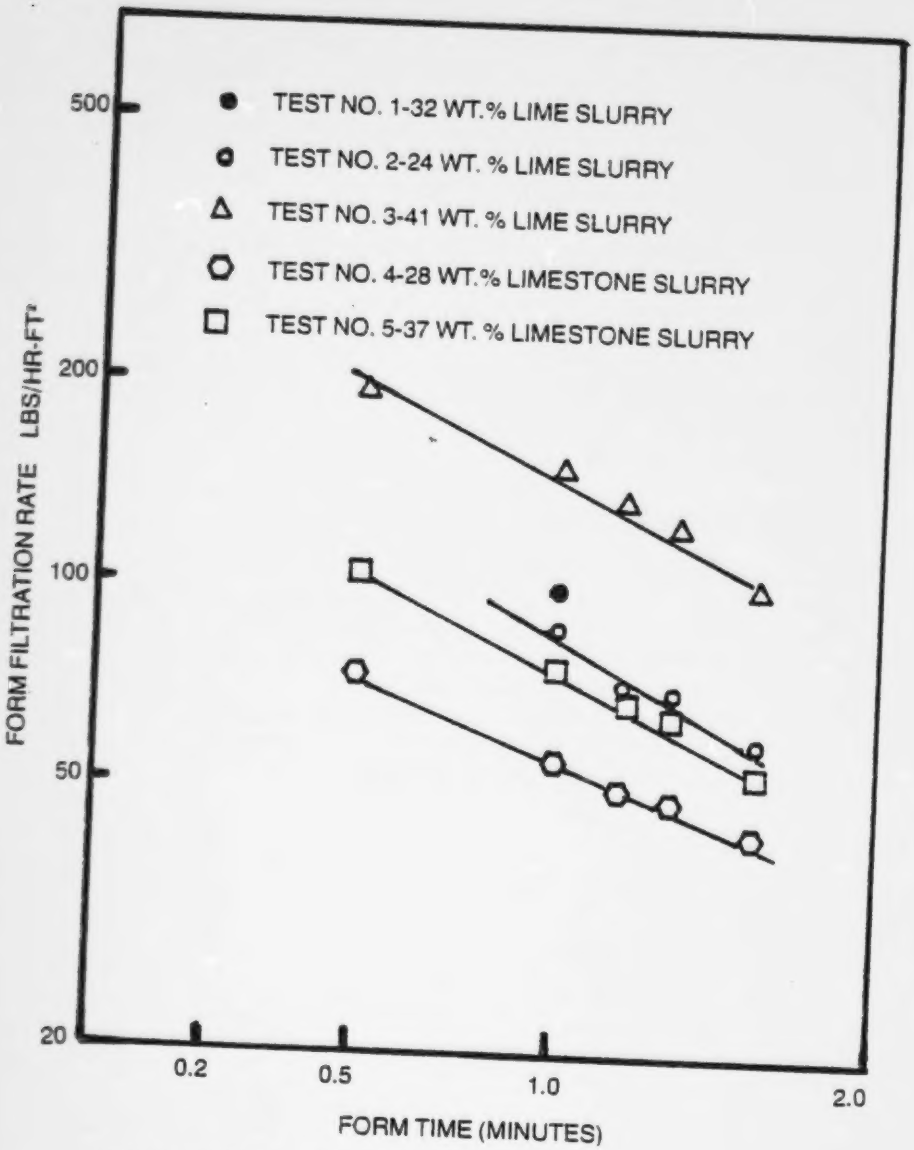

FIGURE 7-3: Filtration rate as a function of form time and slurry concentration .

TABLE 7.3 FILTER LEAF TEST RESULTS

Test #	Initial Slurry Conc. % Solids	Form Filter Rate $lbs/hr-ft^2$ At Form Time 1 min.	1½ min.	2 min.	Filter Cake % Solids At Form Time 1 min.	1½ min.	2 min.
1 (L)	32.32	100.5	--	--	58.4	--	--
2 (L)	24.58	86.9	69.9	58.7	58.0	58.2	58.6
3 (L)	41.47	150.0	124.4	102.4	57.8	59.0	57.3
4 (LS)	28.13	55.8	49.1	43.1	72.6	74.7	74.2
5 (LS)	37.40	75.2	63.9	53.8	76.8	74.0	74.3

TABLE 7.4 SLURRY SOLIDS COMPOSITIONS

Component wt.%	Lime Slurry	Limestone Slurry
Acid Insolubles	6.1	6.7
$CaSO_4 \cdot 2H_2O$	40.4	62.3
$CaSO_3 \cdot 1/2H_2O$	54.8	16.1
$Ca(OH)_2$	0.0	0.0
$CaCO_3$	0.5	14.2
Loss on Ignition	(2.5)	(2.2)
Total (Excluding LOI)	101.8	99.5

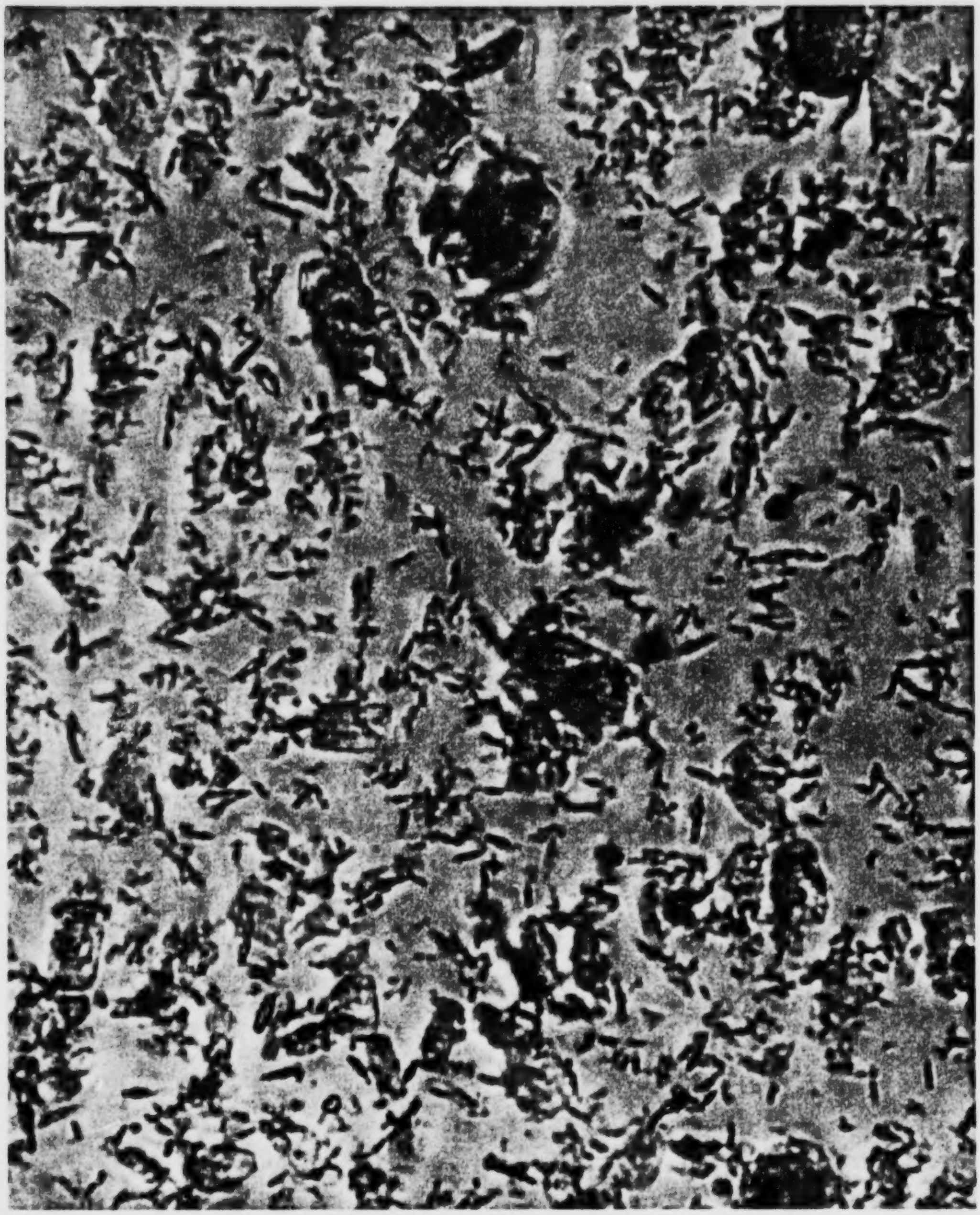

Figure 7-4 A Photomicrograph of Lime Sludge Showing Calcium Sulfite Crystals.

Scale: Approximately 20 microns per inch |——— 20 μ ———|

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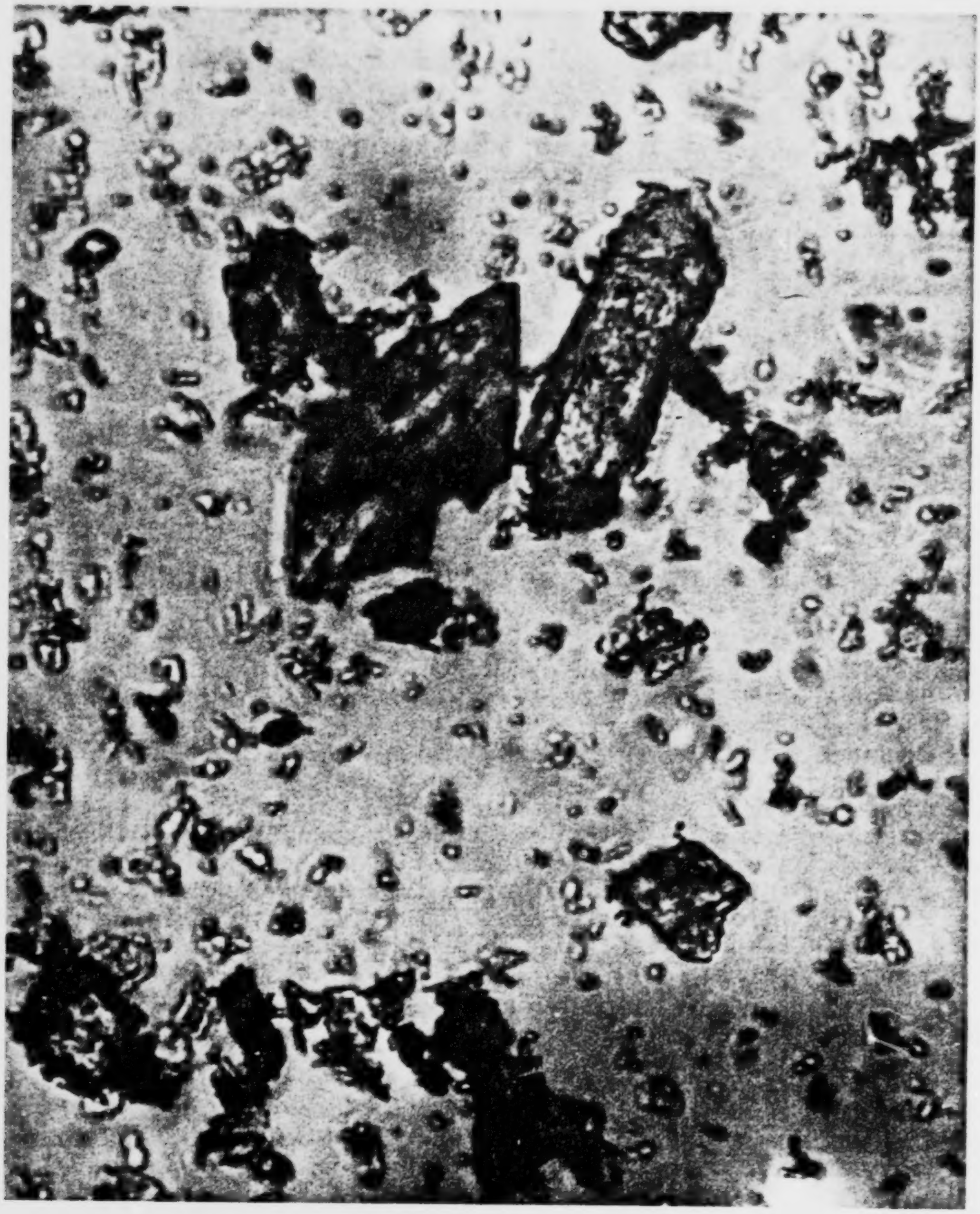

Figure 7-5 A Photomicrograph of Limestone Sludge Showing Gypsum Crystals.

Scale: Approximately 20 microns per inch ├──── 20μ ────┤

Nearly all of the acid insolubles in the slurry solids represent collected particulate matter rather than insolubles from the lime or limestone.[1] The relatively high 2-2.5% loss on ignition shows that substantial carbonaceous material, or soot is present. The presence of soot and fly ash appeared to have minimal influence on lime slurry dewatering and cake solids. The effect, however, on limestone slurry dewatering especially in filtration tests was significant. Dewatering limestone sludges had a high solids content but the dewatering rates were lower than those measured for lime slurries.

TRANSPORTABILITY

Several tests were conducted to determine the ease of transporting and discharging dewatered sludge from trucks or railroad cars. The results are presented in Table 7.5.

Sludge Transport

Slump tests indicate that, above 70 wt.% solids, either lime or limestone slurry is readily transported. Both slump and angle of repose tests show that dewatered lime slurry, below about 70 wt.% solids, is too fluid to hold its shape. Because of its larger particle sizes, limestone slurry is expected to begin to exhibit fluidity below about 60 wt.% solids. Slump tests were performed according to ASTM Method D-2435.

Although laboratory tests provide a good indication of sludge transportability, it would be prudent to carry out full scale tests on a specific sludge to determine the minimum solids content suitable for transport. If dewatered sludge is too fluid to transport, blending with fly ash or other materials would improve transportability and facilitate unloading. If blending was not possible, relatively fluid materials could be transported in containers with provisions to eliminate leakage.

Sludge Unloading

The slide and truckability tests measure the minimum angle at which sludge will move on an inclined plane. These values are measured to indicate the degree of ease or difficulty likely to be encountered when unloading sludge.

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(1) The acid insolubles listed for the reagents in Appendix E are diluted by approximately 3:1 for lime and 1.5:1 for limestone in the sludge produced in the scrubber.

TABLE 7.5 TRANSPORTABILITY TESTS RESULTS

	SAMPLE NO.		
	1	2	3
Scrubber Reagent	Lime	Lime	Limestone
Solids Content, Wt.%	74.9	66.3	83.1
Slump, Inches	0	1-1/8	0
Angle of Truckability, Deg.	90+	90+	90+
Angle of Slide, Deg.	36.1	(1)	37.2
Angle of Repose, Deg.	34.8	(1)	36.0

(1) Sample was too fluid to test.

Sludge is normally transported to disposal or landfill sites in large trucks or railroad cars. A certain amount of compaction normally occurs during transport. The slide tests show that uncompacted, dewatered sludge can be discharged readily from a truck. A minimum angle of 35-40° is required to initiate sludge movement. However, the truckability tests indicated that compacted sludge samples which contain 65-85 wt.% solids may not discharge readily from a truck by gravity alone. Thus, it appears that difficulty may be experienced in discharging compacted loads of sludge even at solids concentration as high as 85 wt.%. Blending the sludge with fly ash is recommended to enhance the discharge of sludge from transport devices. If adhesion of sludge to the transport vehicle is encountered, a layer of fly ash could be placed under the sludge to facilitate unloading.

PHYSICAL/STRUCTURAL PROPERTIES

Two tests were used to determine the strength of dewatered sludge, California Bearing Ratio (CBR) and unconfined compressive strength. The CBR, which is an important parameter for designing structural landfills, is a measure of the load bearing capacity of a confined material. Unconfined compressive strength tests measure the ability of a material to withstand a compressive force. CBR tests were conducted in accordance with ASTM Method D1883-73 and unconfined compressive strength tests according to ASTM D2166.

TABLE 7.6 CBR TEST SUMMARY

	RUN NO.				
	1	2	3	4	5
Scrubber Reagent	Lime	Lime	Lime	Limestone	Limestone
Samples % Solids	80.83	80.83	83.05	83.08	83.08
Pressure at 0.1 Inch Penetration psi	100	133	200	575	383
CBR, % Standard Load	10.0	13.3	20.0	57.5	38.3

The CBR tests showed that the gypsum solids from limestone slurries exhibit more desirable physical properties than those from lime slurries which were predominantely calcium sulfite. Table 7.6 illustrates that limestone solids at similar moisture contents, i.e., 17 to 20%, have a far greater capacity bearing ratio, 38% to 57%, than the lime solids, 10%-20%. However, both the lime and limestone specimens exhibited sufficiently high compressive strengths at the 80+% solids content to support most vehicles.

Unconfined compressive strength tests were run on the two limestone solids samples reported in Table 7.6. The specimens showed a tendency to break apart upon removal from the miter box so more extensive testing was not undertaken. The limestone samples exhibited unconfined compressive strengths of 186 and 307 psi, respectively before showing vertical cracks. These strengths were approximately one-half of those obtained in the CBR tests.

LEACHATE TESTS

Leachate tests were performed on samples of lime and limestone slurry solids to evaluate potential environmental problems associated with the contamination of rain water or runoff percolating through sludge at disposal sites. Leachates were prepared by mixing sludge solids with distilled water. These samples were held at room temperature for two hours under well-stirred conditions to obtain a suitable leachate sample. This procedure, which is used by the State of Indiana, is described in Appendix B. Leachates were analyzed for the chemical components listed in Table 7.7 below.

TABLE 7.7 SLUDGE LEACHATE ANALYSES

Analysis	Lime Leachate	Limestone Leachate
TDS (mg/l)	2,960	2,760
SO_4 (mg/l)	1810.6	1613.1
COD (mg/l)	8.4	6.8
Cl (mg/l)	72.52	48.04
Pb (ppb)	<100	<100
Cd (ppb)	<10	<10
Cr (ppb)	50	50
Hg (ppb)	<25	<25

Leachate compositions from lime and limestone sludges are, within the limits of experimental error, the same. Total dissolved solids (TDS) in the range of 2500-3000 mg/l and the sulfate levels of 1600-1800 mg/l indicate that the leachates were saturated with respect to $CaSO_4$. Chemical oxygen demand (COD) levels of 6.8 and 8.4 mg/l are typical for these types of sludge[1]. Both sulfites in the sludge and organic matter in the fly ash contribute to COD levels.

While the chloride level in the lime leachate is somewhat higher than the limestone leachate, the remainder of the trace elements listed in Table 7.7 are present at essentially the same concentrations in each leachate. Fly ash is thought to be the main source of the trace metals present. Among the three sources of chloride i.e., lime, makeup water and coal the latter is the major contributor.

The leachate analyses indicate no unusual or unexpected results. The constituents found in these leachates are similar in type and concentration to those reported in other studies.

Total dissolved solids, sulfate, chloride and chemical oxygen demand were determined by wet chemical methods. Trace metals were determined using a Jarrell-Ash 850 atomic absorption spectrophotometer.

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(1) P. O. Leo and J. Rossoff, "Control of Waste and Water Pollution from Power Plant Flue Gas Cleaning Systems," EPA-600/7-76-018, October 1976, p. 27.

CONCLUSIONS

- Limestone slurries containing high percentages of gypsum yield more concentrated sludge than lime slurries which were predominately calcium sulfite but dewatering rates are similar.
- Sludge containing more than 70 wt.% solids is readily transportable but may exhibit poor unloading characteristics. Use of fly ash is recommended to improve the transportability and unloading of dewatered sludges.
- Limestone slurry solids because of their high gypsum content exhibit greater compressive strength than those from lime slurries.
- Leachates from RAFB lime and limestone sludges contain typical constituents at concentrations similar to those reported for other FGD sludge leachates.

The above conclusions were based on results obtained during this test program. There have been many other test programs involving comparisons between lime and limestone as scrubbing reagents and the resulting sludges.

The high levels of gypsum (calcium sulfate) observed during this program in the limestone sludges have not been observed in other programs. A comprehensive investigation of oxidation in the R-C/Bahco system would be necessary to determine why these high levels of oxidation occurred. This type of investigation was beyond the scope of this test program.

The effects of temperature, pH, SO_2 concentration and reagent SO_2 stoichiometry on oxidation with lime and limestone were scrutinized. Based on the available data only the system pH varied significantly when limestone was substituted for lime (see Figure 5-6).

The strong effect of the lower pH levels experienced with limestone on increasing oxidation coupled with the very high oxygen content of the flue gas at RAFB (14% or more) are very likely the factors which produced the high levels of gypsum observed during this program.

SECTION 8

OPERATING EXPERIENCE

This section of the report describes the operation of the R-C/Bahco system at RAFB and circumstances which prevented its operation.

EVALUATION OF DOWNTIME

An analysis of the downtime indicates that the system operated with minimal requirements for maintenance under maximum load conditions during the months of December, January and February. It is also obvious that there were substantial amounts of downtime. Figure 8-1 summarizes the overall operation of the system and outages which lasted for more than 24 hrs.

The majority of downtime can be attributed to difficulties with auxiliary equipment, including the booster fan, thickener, second stage slurry pump and lime slaker. Some of the downtime which resulted from the problems with auxiliary equipment was attributable to time involved in obtaining replacement parts. During the test period, spare parts, as a general rule, were not on hand. Brief outages were required to modify spray manifolds and some of the control panel wiring. Heat plant outages for annual maintenance and for tying in new heating equipment are included in the overall analysis because some maintenance or installation work was performed during these periods.

In general, routine maintenance and minor repairs resulted in very short outages and did not contribute significantly to the overall downtime. In addition, some time was lost due to interruptions in the supply of water and electric power to the system.

The downtime associated with auxiliary equipment, including delays resulting from the lack of spare parts, repair time and total downtime, is summarized in Table 8.1.

The following table summarizes the downtime contributed by other sources:

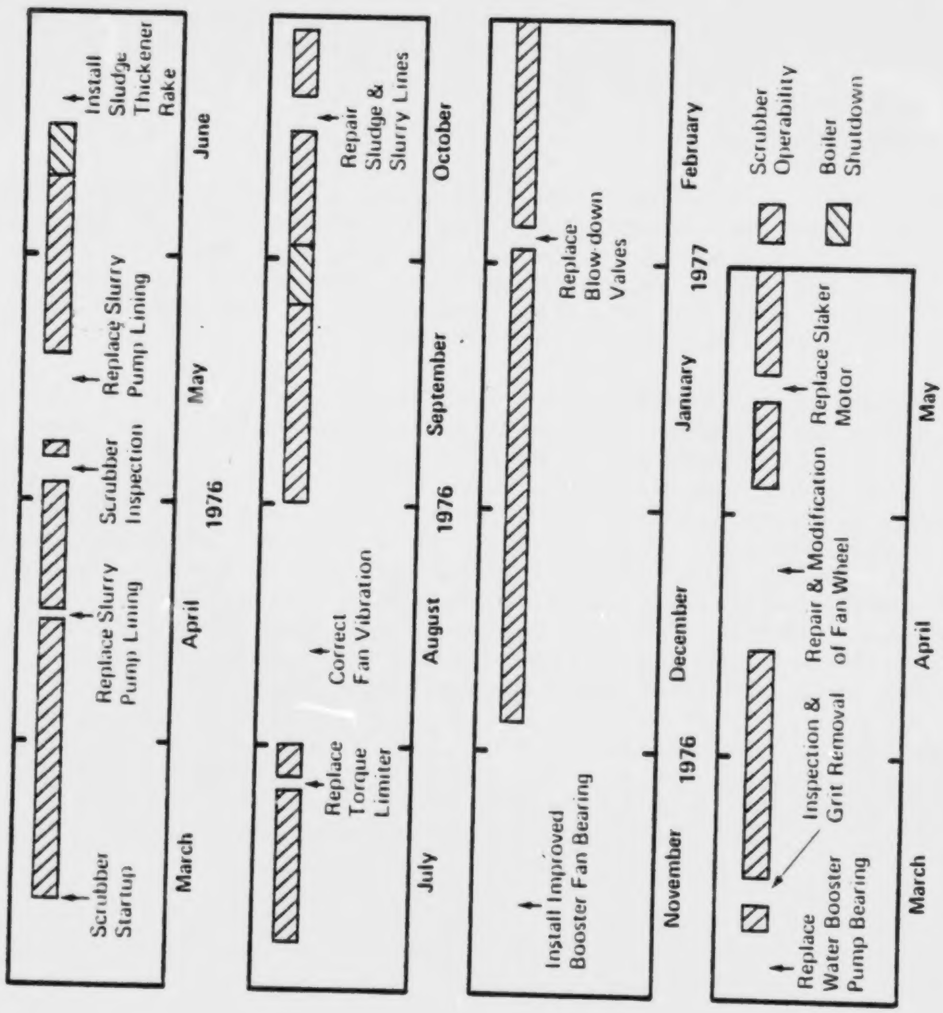

FIGURE 8-1 Downtime related to Auxillary Equipment

TABLE 8.1 DOWNTIME RELATED TO AUXILIARY EQUIPMENT

Time	Estimated Procurement Time Hrs.	% of Total Time	Repair Time Hrs.	% of Total Time	Downtime hrs.	% of Total Time	% of Downtime
Booster Fan	514	(4.7)	2252	(20.4)	2766	(25.1)	57.2
Thickener	471	(4.3)	8	(0.1)	479	(4.4)	9.9
Slurry Pump	252	(2.3)	18	(0.2)	270	(2.5)	5.6
Water Booster Pumps	190	(1.7)	16	(0.2)	206	(1.9)	4.3
Lime Slaker	122	(1.1)	11	(0.1)	133	(1.2)	2.8
	1549	(14.1)	2305	(21.0)	3854	(35.1)	(79.8)

Note: Total time referred to in this table was 11,024 hrs., i.e., the total number of hours from startup in March 1976 to the end of the test program in June 1977.

TABLE 8.2 DOWNTIME FROM OTHER SOURCES

Item	Downtime Hours	% Of Total Time	% Of Downtime
Heat Plant Outages	388	(3.5)	8.0
Modifications	139	(1.3)	2.9
Maintenance	116	(1.1)	2.4
Loss of Utilities	99	(0.9)	2.1
Miscellaneous - inadvertent, unkown frozen lines etc.	234	(2.1)	4.8
Total	976	(8.9)	20.2

The total downtime was 4830 hours or 44.0% of the total of 11,024 hours in the period.

The modifications of the booster fan wheel in April - May 1977 and the improved thrust bearing installed in October - November of 1976 should eliminate the extensive fan outages experienced during the test program.

Thickener related downtime was caused by a fabrication error which in itself was easy to remedy. The extensive downtime resulted from the thickener tank drying out while the necessary shaft extension was being designed and fabricated. The problem can be avoided, if future work on the thickener is required, by keeping the tank full of water.

Downtime associated with the second stage slurry pump was caused by the spare parts situation rather than the time required to work on the pump. Replacement of wet end parts, including rubber liners, shaft sleeves or impellers, requires approximately one or two shifts (8 to 16 hrs). Packing was routinely added or replaced in less than two hours and new drive belts in 2 to 3 hrs. The mill pump is identical to the second stage slurry pump. The only maintenance required for this pump included replacing one set of drive belts and one set of packing.

Downtime associated with the water booster pump and lime slaker was extended significantly because replacement bearings or other parts, which would normally be available, were not on hand. Among the other causes of downtime, heat plant outages were longer than normal because of the new equipment being added to the system. Of the remaining categories, only the downtime for modifications is not likely to recur. Some of the losses of utilities resulted from work in the heat plant. Familiarity with the system should enable operators to reduce downtime in the miscellaneous category.

With major equipment problems cleared up and an adequate stock of spare parts on hand, the system should be able to operate at well over 95% availability.

Each month of operation, from March 1976 to May 1977, is described below, including overall operating or test conditions, operating time for the period and a summary of all interruptions.[1]

MONTHLY OPERATING SUMMARIES

March 1976

The system was started up on February 27, 1976. The flue gas flow rate was set at approximately 40,000 SCFM and the first and second stage pressure drops were set at approximately 7 in. W.C. After approximately 2 hrs. of operation the booster fan started vibrating. Subsequent inspection revealed that the motor side fan bearing had failed causing damage to the fan shaft. The fan was repaired and the system started up again on March 11, 1976. The system operated without incident for the remainder of the month. Performance of the system during this period is described in Section 4.

Operation	504 hours
Interruptions	240 hours
1) Fan bearing failure caused by binding of the oil lubrication rings.	240 hours

April 1976

The system operated at conditions similar to those in March. System variables were changed to obtain qualitative data on the response of the system to adjustments in operating parameters. While these variables were being investigated it became apparent that the second stage venturi pressure drop had become insensitive to adjustments and scrubber particulate performance seemed to deteriorate. On April 14 the system was shutdown and the interior of the scrubber was inspected. The

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(1) A complete log of the operation can be found in Appendix J.

results of this inspection are described in detail later in this section of the report. Grit from the lime slaker, which had filled the slurry pan in the second stage venturi and other areas, was removed from the system before it was restarted. When the second stage slurry pump was started, the rubber lining collapsed. Delays in obtaining a replacement liner for the pump resulted in an outage which lasted until April 29.

Operation	453 hours
Interruptions	267 hours

1) The scrubber inspection and cleanout was caused by indequate grit removal in the lime slaker. Operating procedures were modified to improve grit removal. 15 hours

2) The second slurry pump lining collapse was caused by mismatch between the slurry pump suction line and the slurry pump inlet. An adaptor plate was installed with the new liner to eliminate this problem. 252 hours

May 1976

In May, a series of material balances were conducted to quantitatively determine the overall performance of the system. Complete details of this work can be found in Section 4. For these tests the system was operated at a gas flow of approximately 49,000 SCFM, and a total pressure drop of 22 in. w.c. The inlet gas temperature averaged 320°F.

Early in the month, two plastic external spray manifolds on the upper part of the scrubber were removed. These were replaced by stainless steel manifolds built into the shell of the scrubber.

A few days later, dirt contaminated the motor side fan bearing resulting in a failure. Rebabbiting of the bearing was necessary since a spare was not on hand.

Operation	445 hours
Interruptions	299 hours

1) Replacement of water spray manifolds 57 hours

2) Failure of the booster fan motor side bearing was caused by dirt entering the bearing. After the repair was completed, instrument air purges were added to the bearings to prevent dirt from entering them. 226 hours

3) Unknown 16 hours

Operation	459 hours
Interruptions	285 hours

1)	Resealing the wood thickener tank.	159 hours
2)	Procuring and replacing the lime slaker torque limiter.	43 hours
3)	Miscellaneous maintenance, training and loss of utilities	9 hours
4)	High fan vibration.	58 hours
5)	Replacing sludge pump diaphragm.	16 hours

August 1976

During the month of August the fan vibration which began in July was analyzed. This analysis revealed that the concrete outboard fan bearing support had become separated from the slab upon which it rested. External braces for the bearing support were designed, fabricated and installed to rectify this problem. When the system was started up near the end of August, the motor on the lime slaker grit conveyor failed. These problems resulted in a shutdown for essentially the entire month of August.

Operation	16 hours
Interruptions	728 hours

1)	Diagnosis of the problem and repair of the fan support.	701 hours
2)	Replacement of the grit conveyor motor. The motor was obtained from a local distributor.	19 hours
3)	Miscellaneous.	8 hours

September 1976

In September the system operated at conditions similar to those for July. Performance tests for SO_2 removal efficiency were conducted. The results of these tests are presented in Appendix J. The level controller in the lime dissolving tank malfunctioned causing some downtime during the month. During the last week in September the heat plant was shutdown to tie in piping for a new hot water generator. The fan alignment was checked and adjusted and the fan was rebalanced during this outage.

Operation	532 hours
Interruptions	188 hours

1)	Heat plant outage and realigning and balancing the booster fan.	142 hours
2)	Lime dissolver level control malfunction.	40 hours

3) Maintenance.	6 hours

October 1976

The outage for tying in the new generator extended three days into October. When the system was started up the load on the heat plant required an increase in gas flow to the scrubber. In the middle of the month one of the sludge pumps stopped operating when the hose to the pond was full of high density (50+% solids) sludge. The spare hose had already been plugged by a similar mishap and had not been cleaned. The hose was removed from its casing and unplugged. Shortly after the system was restarted a slurry hose which runs from the first stage liquid seal to the lime dissolver developed a leak. A stainless steel coil had been placed inside this hose to prevent it from collapsing. This coil had a sharp end which worked its way through the hose causing the leak. The damaged section of the hose was replaced with a stainless steel pipe and the coil was modified to prevent the problem from recurring. During the last week in October, the fan began vibrating and the system was shutdown.

Operation	451 hours
Interruptions	293 hours
1) Heat plant outage.	78 hours
2) Unplugging the sludge line to the pond.	18 hours
3) Fabrication and installation of a stainless steel line to repair the damaged slurry line.	64 hours
4) Loss of utilities - water and electric power.	47 hours
5) Miscellaneous.	8 hours
6) Fan vibration.	78 hours

November 1976

The entire month of November as well as several days in December were spent replacing the booster fan bearing on the motor side and repairing the fan shaft. Problems in obtaining replacement parts contributed substantially to the length of this outage.

Operation	0 hour
Interruptions	720 hours

December 1976

The system functioned smoothly throughout the month. The inlet gas flow rate was 50,000 scfm and the scrubber inlet temperature reached 460°F, typical high-load winter operating conditions. The first phase of the process variable screening study using lime as a reagent was undertaken. Both SO_2 and particulate removal efficiencies were evaluated while eight primary operating parameters were varied. These tests are described in detail in Sections 5 and 6 of this report.

Approximately three days in December were lost while completing the repair to the fan bearing. Aside from minor outages due to the losses of water and plant air and some frozen instrument air lines availability of the system was nearly 100%.

Operation	623 hours
Interruptions	121 hours
1) Completion of fan bearing repairs.	82 hours
2) Loss of water and electric power.	24 hours
3) Frozen air lines.	9 hours
4) Maintenance and miscellaneous.	6 hours

January 1977

The system ran very smoothly in January. Despite record breaking sub-zero weather, availability was approximately 94%. The scrubber operated at its rated capacity, approximately 50,000 scfm, as it had in December. SO_2 test work planned for January was cancelled due to the extreme weather conditions. Frozen air lines which supply instrument air to operate the scrubber blowdown valves caused some downtime. In addition, some time was lost repairing frozen water lines.

Operation	699 hours
Interruptions	45 hours
1) Frozen air lines and cleanout of accumulated grit due to the inability to operate the blowdown valves	30 hours
2) Repair of frozen water lines.	9 hours
3) Maintenance and miscellaneous.	6 hours

February 1977

The system functioned very well for the third consecutive month at operating and ambient conditions similar to those in December and January. In February the system operated at slightly above the design gas rate. Testing was resumed and the variable screening tests started in December were completed. The blowdown valves again were the most significant source of downtime. During this month, however, time was spent replacing the air operated valves with more reliable manual valves.

Operation	588 hours
Interruptions	84 hours
1) Blowdown valve blockages and replacement of these valves.	70 hours
2) Repair of frozen water lines.	4 hours
3) Maintenance and miscellaneous.	10 hours

March 1977

In March the lime reagent testing was completed. Prior to starting this work, the system was inspected and the grit which had accumulated over previous months from the inoperative blowdown valves was removed. Early in March a defective bearing in the water booster pump was replaced and some wiring changes were made in the control panel.

Operation	465 hours
Interruption	279 hours
1) Procuring and replacing the water booster pump bearing.	206 hours
2) Rewiring control panel.	39 hours
3) Inspecting the system and removing accumulated grit.	30 hours
4) Miscellaneous.	4 hours

April 1977

Work on the particulate removal efficiency tests begun in December was completed in April. The results of these tests are described in Section 6 of this report. In April limestone was substituted for lime as the SO_2 scrubbing reagent. Heat plant loads were significantly lower than in prior months. The system performed smoothly until the middle of the month when booster fan vibration levels rose. An inspection revealed cracks in the rim of the fan wheel. This assembly was removed and subsequently modified by removing the rims and reducing the wheel diameter from 81 inches to 76 inches. The resulting outage began in mid April and lasted until early May.

Operation	218 hours
Interruptions	439 hours
1) Repair and modification of the fan wheel.	430 hours
2) Maintenance and miscellaneous.	9 hours

May 1977

In May a series of limestone reagent SO_2 performance tests were completed. This work was the final phase of the field test program for this contract at RAFB. The results of these tests are described in Section 5 of this report.

The fan repair was completed in the first part of May. Some additional downtime resulted from repairs to a fan bearing resistance temperature detector which was disturbed during the fan repairs. In addition, a motor on the lime slaker paddle drive was replaced.

Operation	435 hours
Interruptions	309 hours
1) Complete fan repairs.	201 hours
2) Repair fan bearing RTD.	30 hours
3) Procure and replace lime slaker motor.	71 hours
4) Maintenance and miscellaneous.	7 hours

SCRUBBER INSPECTIONS

Scrubber inspections were an integral part of the program to monitor scrubber performance. A thorough internal inspection was made in April of 1976, approximately one month after start-up, and a follow-up inspection was made two months later in June. Subsequently, inspections were made when opportunities were available during outages up to the end of the test program in June of 1977. These inspections helped to determine the effectiveness of the water makeup system in keeping key areas in the scrubber clean and provided an opportunity to see if any other problems were developing. The inspections revealed that solids had accumulated in the following areas as shown in Figure 8-2 during the test program.

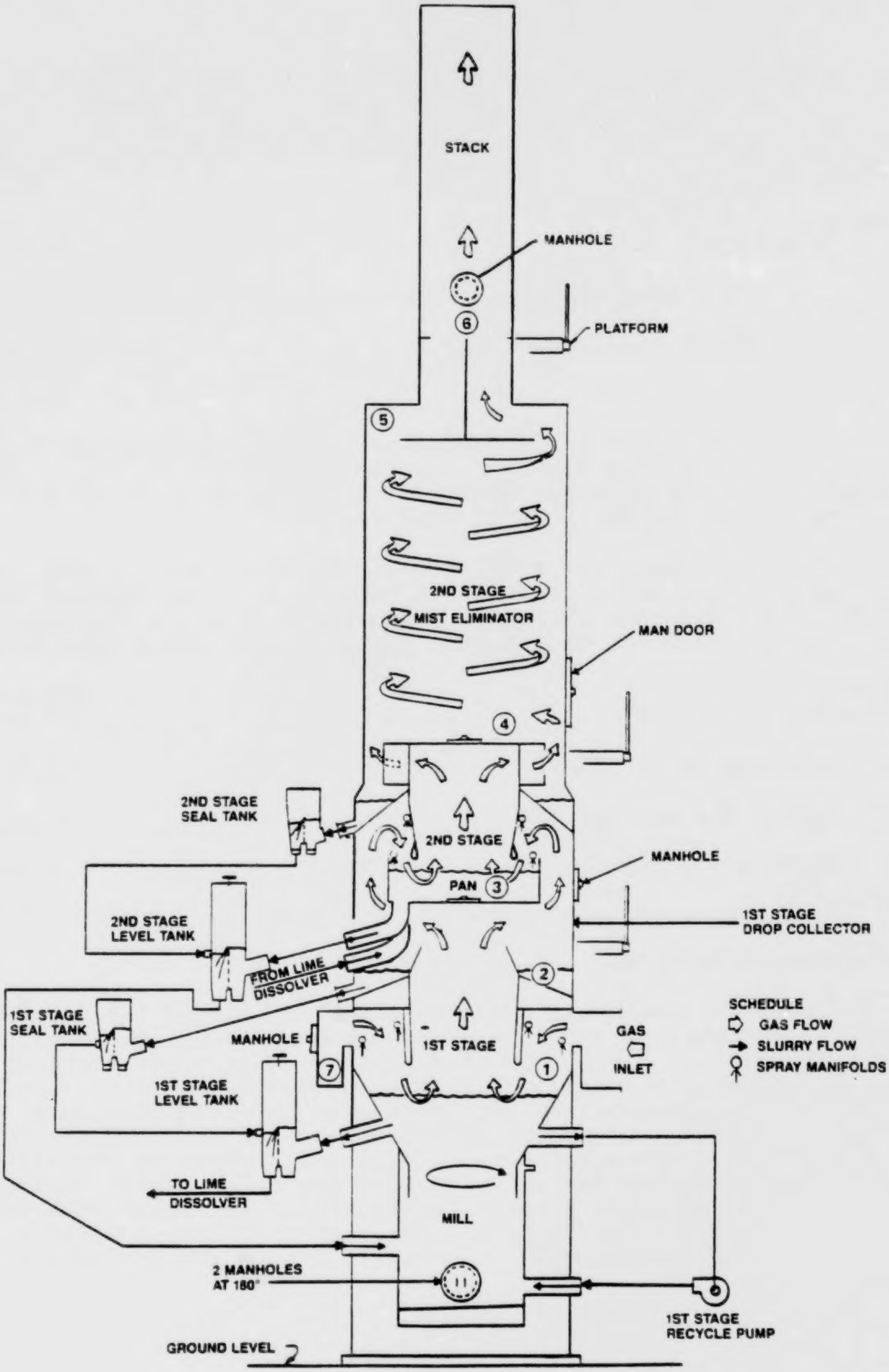
STACK
MANHOLE
⑥
PLATFORM
⑤
2ND STAGE
MIST ELIMINATOR
MAN DOOR
④
2ND STAGE
SEAL TANK
2ND STAGE
PAN ③
MANHOLE
1ST STAGE
DROP COLLECTOR
2ND STAGE
LEVEL TANK
FROM LIME
DISSOLVER
②
SCHEDULE
GAS FLOW
SLURRY FLOW
SPRAY MANIFOLDS
1ST STAGE
SEAL TANK
MANHOLE
⑦
1ST STAGE
①
GAS
INLET
1ST STAGE
LEVEL TANK
TO LIME
DISSOLVER
MILL
2 MANHOLES
AT 180°
1ST STAGE
RECYCLE PUMP
GROUND LEVEL

Figure 8-2 Bahco Scrubber Module

1. Scrubber inlet wet/dry zone
2. Bottom of the 1st stage drop collector
3. 2nd stage venturi slurry pan
4. Top of the 2nd stage venturi spin assembly
5. Top of the 2nd stage mist eliminator
6. Straightening vanes in the stack and the stack wall
7. Bottom of the flue gas inlet manifold

April 1976 Inspection

The inspection in April 1976 revealed the following:

Scrubber Inlet Wet/Dry Zone

The solids in the wet/dry zone in the inlet area were a mixture of dried slurry and fly ash which had accumulated on the spray manifold in this location. Since there was no reduction in the area of the flue gas inlet ports and no appreciable decrease in flow area between the scrubber wall and the first stage venturi this material was left in place.

Bottom of the First Stage Drop Collector

A coarse sandy or gritty material covered the bottom of the drop collector. The buildup was approximately 18 inches deep opposite the slurry outlet and sloped down towards the outlet. This material was left in place since slurry flow was not impeded.

Second Stage Venturi Slurry Pan

The pan in the second stage just below the venturi had a substantial accumulation of coarse sandy material similar to that in the first stage drop collector. This material had accumulated to the point that the second stage venturi performance was adversely affected. Since the pan was nearly full to the rim (about 24 inches deep) over more than half of its area, allowing flue gas to flow through the venturi with little slurry pickup this material was removed.

Top of the Second Stage Venturi Spin Assembly

The buildup on top of the second stage spin assembly was a soft muddy material several inches thick. This material which appeared to be typical scrubber solids which had settled out in a stagnant area in the centrifugal mist eliminator was left in place.

Top of the Second Stage Mist Eliminator

The solids which were observed in the top of the second stage mist eliminator had essentially filled in the corner at the top of the mist eliminator just above the spray nozzles. This material was left in place.

Straightening Vanes in the Stack and the Stack Wall

The material which accumulated in the stack area appeared to be a mixture of fly ash and slurry which had deposited and recystallized. The buildup on the stack wall was approximately ¼ inch thick. The buildup on the straightening vanes was approximately ½ inch thick. These accumulations were left in place.

The accumulation in the second stage venturi slurry pan location (3) was the only accumulation which posed any problem to the operation of the scrubber. The pan was emptied and solids were dislodged from the wet/dry zone and removed from the system. This operation took approximately 15 hours. Subsequent investigation into the cause of the accumulation in the pan revealed that the lime slaker grit removal circuit was not operating effectively and virtually all of the gritty material in the unslaked lime was entering the scrubber. The grit removal circuit was readjusted to remove this material. Figure 8-3 shows the scrubber internals in the second stage. A light coating of solids had accumulated on the venturi spray manifold and shell. This coating which was observed during subsequent inspections remained essentially unchanged during the entire fourteen month test period.

June 1976 Inspection

A follow-up inspection during an annual heat plant outage in June 1976 revealed the following:

Scrubber Inlet Wet/Dry Zone

The inlet wet/dry zone had an accumulation which was very similar to that observed in April. Again, since there was no reduction in the gas inlet port area or in the flow area to the first stage venturi this material was left in place.

Bottom of the First Stage Drop Collector

There was a slight increase in the amount of material located in the first stage drop collector compared to the amount observed in April. Again, this material was left in place.

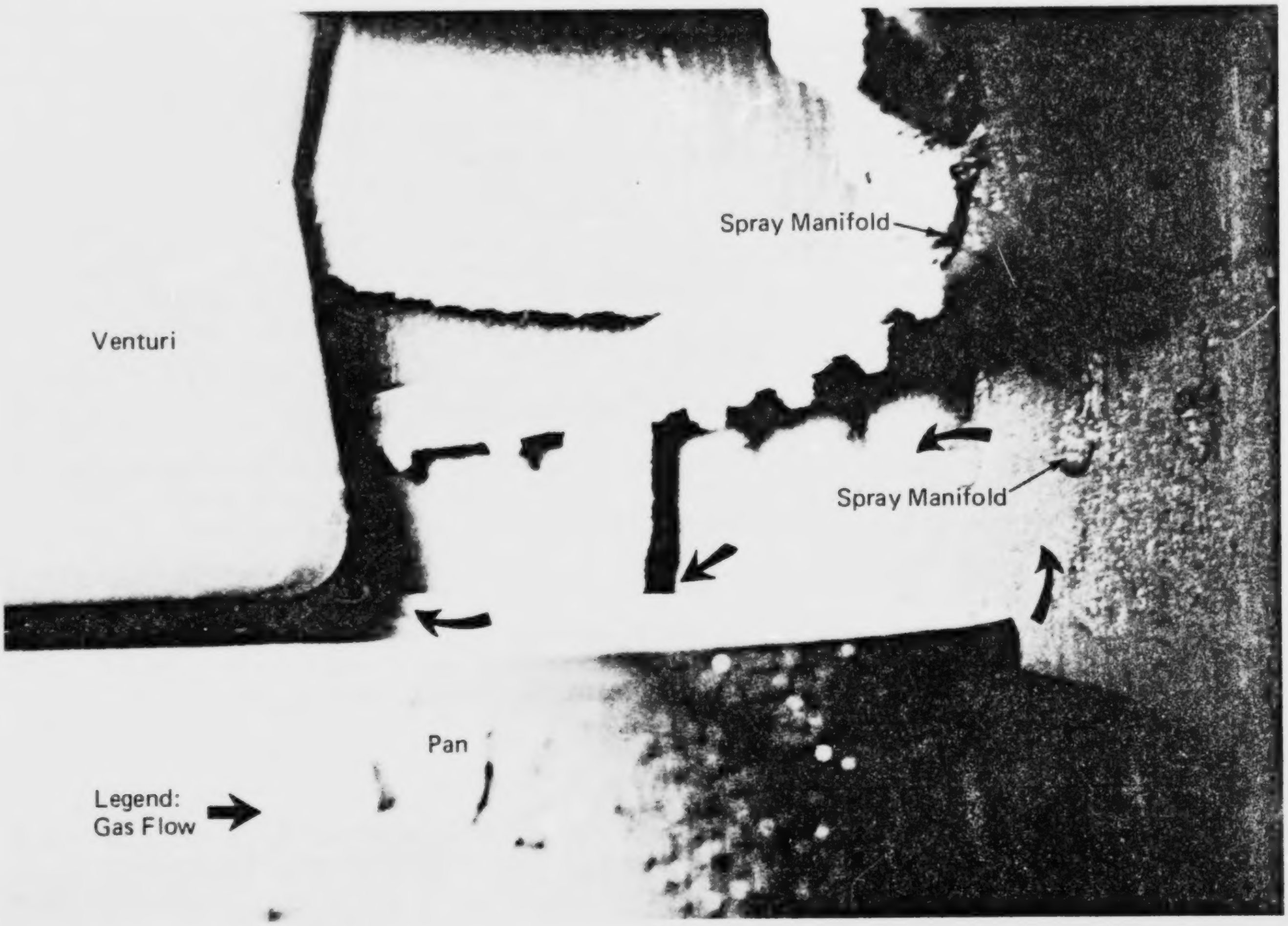
Spray Manifold
Venturi
Spray Manifold
Pan
Legend:
Gas Flow

Figure 8-3 R-C/Bahco Scrubber Internals Showing the Venturi, Pan and Spray Manifold in the Second Stage

Second Stage Venturi Slurry Pan

This area had accumulated an insignificant amount of gritty material which partially covered the bottom of the pan. This material was left in place. The revised lime slaker operating procedures had eliminated the grit accumulation problem and the resulting rapid buildup which had occurred in April.

Top of the Second Stage Venturi Spin Assembly

The muddy accumulation at this location was thicker than it was in April. It appeared to be the same type of material observed earlier, again it was left in place.

Top of the Second Stage Mist Eliminator

The solids which accumulated in this area did not seem to be any heavier than the deposit which had been observed in April. This indicated that a stable accumulation had occurred. Again, the material was left in place.

Straightening Vanes in the Stack and the Stack Wall

This area continued to accumulate material. The straightening vanes had approximately 1-1/2" of buildup and the stack wall approximately 3/4". This material was left in place.

Bottom of Flue Gas Inlet Manifold

Between April and May some flooding occurred in the first stage causing slurry to enter the flue gas inlet manifold. This flooding resulted in a deposit of dried solids approximately 4" deep. This material was left in place.

September 1976 Inspection

The heat plant was shut down again in September 1976 to tie in new hot water distribution lines. The scrubber was inspected again at this time.

Additional accumulations of solids had occurred in two locations. The straightening vanes, location 6, had accumulated further solids which caused an undesirable pressure drop of approximately 2 in. W.C. The material, which was 2 to 4 in. thick, was removed at this time. The bottom of the flue gas inlet manifold, location 7, had accumulated more solids from additional overflow from the first stage venturi. The solids were 8" to 10" deep at this time. Since the continued flooding of the first stage and the resulting buildup were unacceptable occurrences, they had to be eliminated. Subsequent investigation revealed that operation of the first stage at pressure drops above 12" to 13" w.c., coupled with a second stage slurry pumping rate more than 50% higher than the design rate of 2600 gpm, caused flooding when the gas flow was reduced below design rates or the booster fan was shut down. In order to eliminate this problem, the speed of the second stage slurry pump was decreased to reduce the slurry pumping rate to design levels. In addition, an interlock was added to stop the second stage slurry pump when the booster fan shut down.

March 1977 Inspection

A somewhat unusual winter caused a number of freezing problems in instrument air supply lines. These freezeups rendered the scrubber blowdown valves inoperative. This resulted in a substantial accumulation of gritty material in the system, partially blocking the scrubber's slurry outlets. In March of 1977, in preparation for a continuation of the SO_2 and particulate tests, the scrubber was inspected. The bottom of the first stage drop collector and the second stage venturi pan had accumulated quantities of gritty material which were substantial enough to require removal. In addition, the scrubber inlet and straightening vanes in the stack were cleaned.

The Scrubber Inlet Wet/Dry Zone

This area had a buildup which appeared to be similar to that observed in June of 1976. Again there was no reduction in gas flow area. This material was dislodged and removed.

Bottom of the First Stage Drop Collector

The material which deposited in this area as a result of the inoperative blowdown valves was a mixture of muddy and gritty material as much as 30 inches deep. This material settled out when the slurry outlet from this part of the scrubber was obstructed by grit accumulated above the inoperative blow down valves. This material was removed from the scrubber.

Second Stage Venturi Pan

The retention of gritty material in the system caused by the inoperative blowdown valve, resulted in an accumulation which half filled the 24" deep pan. This accumulation could have adversely affected the operation of the second stage venturi at low pressure drops; therefore, it was removed from the scrubber.

Straightening Vanes in the Stack and the Stack Wall

Again, a crystalline deposit occurred in this area. These deposits were 1 to 2 in. thick on the straightening vanes and 1/2 in. thick in the stack. At this time, these deposits were removed.

The cleanout of the four areas described above took approximately 15 hours.

June 1977 Inspection

In June of 1977, after completion of the test program, the system was inspected during an annual heat plant outage. The material which had accumulated in the bottom of the flue gas inlet manifold during the first six months of operation was removed. As expected, the inspection revealed the following:

Scrubber Inlet Wet/Dry Zone

The usual accumulation observed in the past was present. This material was not removed.

Bottom of the First Stage Drop Collector

Some muddy deposits which were thickest opposite from the slurry outlet had accumulated. These deposits which were left in place tapered off near the outlet leaving the slurry flow passage 100% open.

Second Stage Venturi Slurry Pan

A small amount of gritty material which partially covered the bottom of the pan was observed. This material was left in place.

Top of the Second Stage Venturi Spin Assembly

A layer of soft deposits which were approximately 6" thick was observed on top of the venturi. This material was left in place.

Top of the Second Stage Mist Eliminator

As it appeared in earlier inspections, the upper corner was filled with solids. This material was left in place.

Straightening Vanes in the Stack and the Stack Wall

As observed earlier, a buildup had accumulated on the vanes which was approximately 1/2" thick. In addition, approximately 1/4" of accumulation had occurred in the stack. This material was left in place.

Conclusions

Three areas which can result in deterioration of scrubber performance include infiltration of grit into the system through the lime slaker, inadequate operation of the scrubber blowdown valves, and the slow accumulation of solids in the straightening vanes and stack.

The infiltration of grit can be kept to a minimum by paying close attention to the operation of the lime slaker grit removal circuit. The blowdown valves need to be operated two to four times a shift, depending on scrubber load, to prevent an accumulation of solids in the slurry outlets. The straightening vanes and stack wall accumulate some material which must be checked on a semiannual basis. Removal of this material is required when the accumulation approaches 3" - 4" in thickness in the vanes. The rate of accumulation can be minimized by operating the second stage venturi to minimize the possibility of slurry droplet carryover (i.e., by operating at pressure drops below 12" w.c.). Figure 8-4 illustrates the buildup which accumulated on the vanes in the stack area during approximately six months of operation. It is important to note that the reduction in gas flow area even at this point is relatively insignificant and did not adversely affect the operation of the scrubber.

The foregoing indicates that there are no significant problems related to the accumulation of solids in this system. The scrubber has the ability to tolerate substantial accumulations of solids resulting from external operating problems before scrubbing performance is adversely affected. In addition any deterioration in performance, if it occurs, is gradual and can be rectified at a convenient time.

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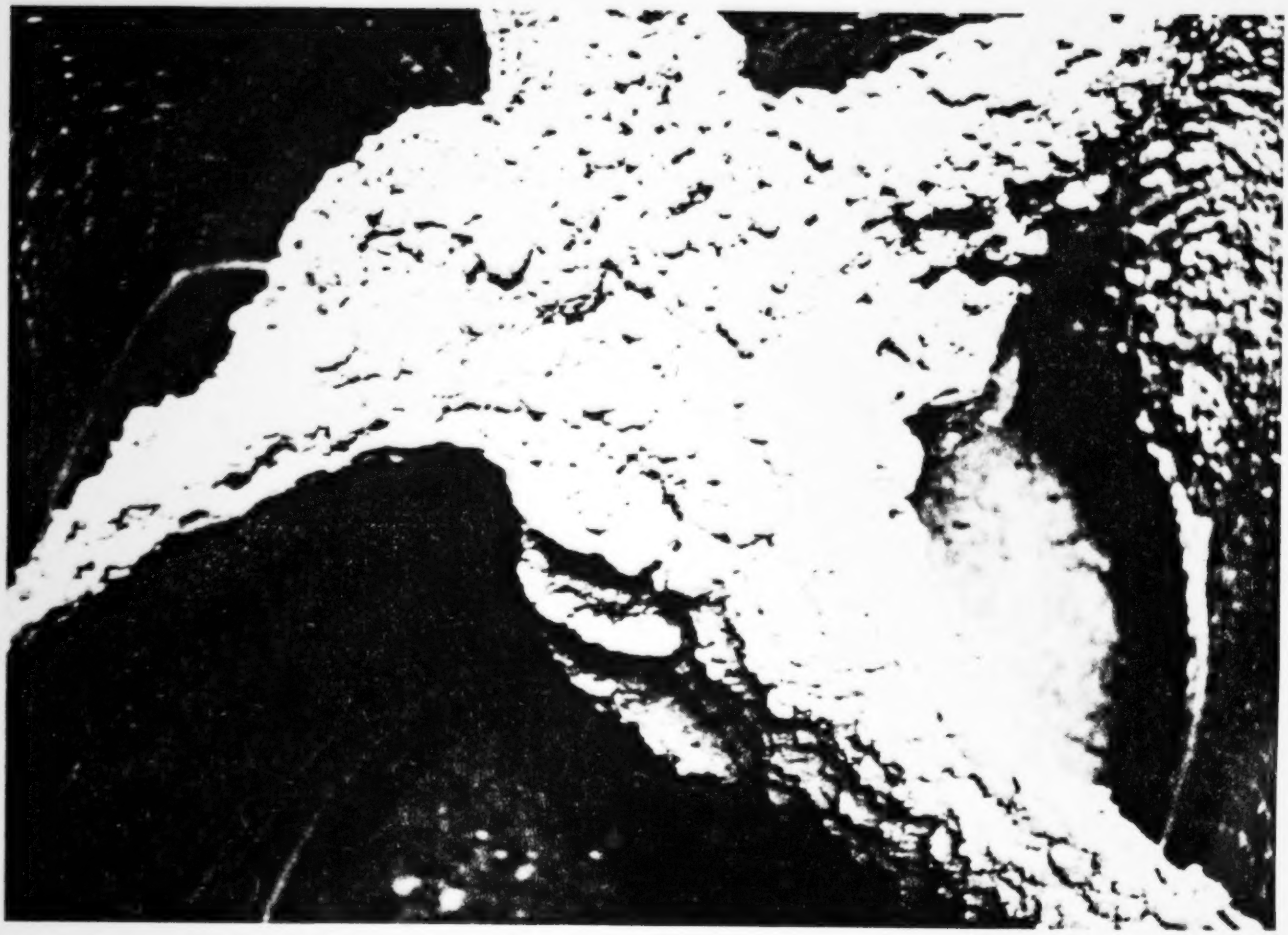

Figure 8-4 Buildup on the Vanes in the Stack Area After Six Months of Operation

SECTION 9

OPERATING AND MAINTENANCE COSTS

In order to arrive at operating and maintenance costs for the R-C/Bahco system, data was collected during the period from March 11, 1976 to May 31, 1977. This data included information on the consumption of power, water, and chemicals as well as operating and maintenance costs.

OPERATING COSTS

During the test period, the scrubbing system treated flue gas from the combustion of 27,216 tons of coal; sulfur content ranged from 2 to 3.5% and averaged 2.5%. The total operating cost, summarized in Table 9.1, for utilities, reagent, supplies and operating labor was $5.07/ton of coal burned. These costs were projected to be $5.92/ton of coal burned and a cost ceiling of $7.56/ton, based on current reagent and power cost, was guaranteed in the contract. Maintenance, labor and materials added $0.21 to the cost of $5.07/ton of coal burned. An operating cost of $4.06/ton can be achieved if limestone is used or the scrubbing reagent and fan settings and makeup water consumption are optimized.

TABLE 9.1 OPERATING COST SUMMARY

Power	Units	Unit Cost	Total Cost
Booster	3,065,000 KW	$0.024/KWH	$ 73,560
Auxiliary Equipment	602,500 KW	$0.024/KWH	14,460
Water			
Potable water	4,448,120 Gal	$0.36/M gal	1,601
Well water	1,768,700 Gal		
Chemicals			
Lime	721 Tons	$40.35/ton	29,092
Limestone	130 Tons	$12.72/ton	1,654
Labor			
Operating labor	1,860 man-hrs	$7.52/man-hr	13,987
Supervision	25% of operating	labor (estimate)	3,497
		Total	$137,851

Cost per ton of coal = $5.07

Data in Table 9.1 on operating labor requirements and rates, lime and limestone deliveries, coal consumption and water and power costs were obtained from the USAF.

Power Consumption

As part of the test program, devices to measure power consumption of the booster fan as well as other equipment in the system were installed. These are listed in Table 9.2. Pumps, controls, lighting, heat tracing, control house heating and cooling, etc. were included.

TABLE 9.2 EQUIPMENT POWER REQUIREMENTS

	No. Used	Total KW or (H.P.)
Booster Fan	(1)	518 (700)
Slurry circulating pumps	(2)	74.0 (100)
Makeup water booster pump	(1)	22.4 (30)
Thickener	(1)	1.5 (2)
Lime Slaker	(1)	2.2 (3)
Freeze Protection		7.5 (10)
Other misc. equipment		
Lighting		

Power consumed by the auxiliary equipment, as listed in Table 9.1, is typical for this type of system. The booster fan power consumption, however, is substantially higher than normal. Several factors contributed to the high fan power consumption, including the extra capacity required for flexibility in running this test program as well as the need to run higher than normal pressure drops to cope with high levels of soot.

In order to insure that the capacity of the system would not be limited by fan capacity, a fan with extra pressure and flow capacity requiring a 700 H.P. motor was installed. A 500 H.P. model would normally have been selected for this application. Under normal circumstances the scrubber would have been operated at at total pressure drop of approximately 15 in. W.C. Routine operation at total pressure drops over 20 in. W.C. to attempt to maximize the removal of soot resulted in a significant increase in power consumption and a power cost penalty of approximately $14,000. Near the end of the test program the fan was modified to reduce its pressure capacity from 32 to 25 in W.C. This modification will alleviate some throttling losses but the major power cost penalty will be eliminated only when improvements in the heat plant result in better combustion.

Water Consumption

The consumption of potable water did not contribute significantly to the overall cost of operating the system. This cost, however, could be reduced by more efficient water management. The reuse of booster fan bearing cooling water for lime slaking or on slurry pump seals and optimizing lime slaker water consumption could reduce potable water consumption to approximately half of the present rate of 159 gpm.

Chemical Consumption

The average stoichiometry for the test period based on the total coal consumption was approximately 0.50 moles of reagent per mole of SO_2. During the test period 90% of the reagent used was lime, the balance was limestone.

The average stoichiometry of 0.5 was adequate for 2.5% sulfur coal to meet the existing emissions standards of 2.2#SO_2 per MM Btu of coal burned.

If limestone were substituted for lime, this SO_2 emission standard could be achieved at a stoichiometry of 0.55. Substituting limestone for lime during the test program would have resulted in a reagent cost reduction of $14,000.

Labor Costs

Operating manpower needs were met by a scrubber technician, who operated the system on day shift during the week while performing routine maintenance tasks, and heat plant personnel who operated the system, in addition to running the heat plant, on off shifts and weekends.

The scrubber technician handled routine operation and maintenance items including lubrication, instrumentation and electrical equipment in addition to routine mechanical maintenance such as adjusting pump packings and belt tensions. Routine operation of the scrubber includes monitoring the system's auxiliary equipment and periodically removing gritty material from the lime slaker grit removal circuit and the scrubber blowdowns.

Since the USAF at Rickenbacker does not keep a separate account of supervision requirements, the cost of supervision attributable to scrubber operation was estimated to be 25% of the operating labor cost.

Optimum Operating Costs

Table 9.3, summarizes a projected cost for operating the R-C/Bahco system at RAFB at optimum conditions, for a period comparable to the test period.

TABLE 9.3 OPTIMUM OPERATING COSTS

Power	
Fan	$ 59,500
Auxiliary Equipment	14,460
Water	
Potable	800
Well	----
Chemicals	
Lime	32,375
Limestone (if used instead of lime)	(18,375)
Labor	
Operating labor	13,987
Supervision	3,497
Total for lime	$142,990

Cost per ton of coal $4.58 ($4.06 for limestone)

MAINTENANCE COSTS

The maintenance costs presented in this section include items related to normal maintenance. Problems such as fan repairs which were handled on a warranty basis, and are not likely to recur, have not been included.

The following labor and materials costs, for routine maintenance listed in Table 9.4, were incurred during the test period:

TABLE 9.4 MAINTENANCE LABOR AND MATERIAL COSTS

Maintenance Labor	
Repair lime feeder	$300.
Repair sludge control valve	100.
Replace slurry pump shaft, bushing and sleeve	800.
Repair water booster pump	200.
Scrubber maintenance	600.
Rebuild delumper	1000.
Service Dupont Analyzer	400.
Clear lime unloading line	100.
Sub-total	$3,500
Maintenance Material	
Replace slurry pump belts	50.
Replace sludge pump diaphragm	20.
Replace fan bearing oil	10.
Repack slurry pumps	120.
Replace 1½ in. pinch valve liner	75.
Replace slurry pump bushing & sleeve	500
Rebuild delumper	200.
Replace slaker torque limiter	10.
Replace pH probe	250.
Touchup paint	25.
Recorder ink & paper	600.
Sub-total	1,860.
Total Maintenance Cost (Labor and Material)	$5,360

The maintenance labor listed above does not include the time spent by the scrubber technician in performing routine adjustments, oil changes, etc. However, this time was included in the operating cost summary under operating labor.

As indicated by the modest maintenance requirements, the system is relatively simple to maintain and should prove to be relatively trouble-free.

RECOMMENDED OPERATING CONDITIONS

Reagent Selection

Lime was originally chosen as the SO_2 scrubbing reagent for RAFB. This choice was made to insure that SO_2 emissions would be well within the allowable limits in effect at that time, i.e. 1.0 pounds of SO_2 per million Btu gross heat input. Dependable SO_2 emissions of 0.83 pounds SO2 per million Btu at a stoichiometry of 0.87 were achieved using lime.

Since that time new air pollution requirements have been proposed to allow emissions of 2.2 pounds per million Btu. Either lime or limestone can be used effectively to meet this proposed standard. However, lime delivered at the site costs $40.35 per ton while limestone costs $12.72 per ton. Economics favor limestone even though nearly double the weight of limestone is required to compensate for the higher molecular weight and lower utilization (85%) expected for limestone. The amount of lime with 90% available CaO required to treat SO_2 produced by burning one ton of 3.5% sulfur coal costs $1.88 while limestone with 95% available alkalinity can produce the same result for $1.05.

Limestone is easier to feed into the system since it is not hygroscopic and requires no slaking. In addition, limestone is less hazardous since it does not exhibit the caustic properties of lime dust and slurries which can cause damage to sensitive tissue. The fact that the use of limestone results in approximately 25% more weight of sludge due to higher gypsum levels and the presence of unreacted limestone is offset by the fact that limestone sludges settle more rapidly and produce higher final solids content than lime sludge. These factors will essentially balance the excess weight resulting in an equivalent volume required for storage, i.e., pond life at RAFB will not be decreased by switching to limestone. Again, it is important to note that the high gypsum content of the limestone sludge results from the particular circumstances at RAFB which produce high levels of oxidation.

Slurry Pumping Notes

The second stage slurry pumping rate should be set for a flow of 2200 to 2400 gpm to maximize limestone utilization and SO_2 removal efficiency.

Flue Gas Notes

Flue gas flow rates should be maintained between 35,000 and 55,000 SCFM as heat plant load variations permit, to avoid unstable operating conditions which result in high particulate emissions.

Venturi Pressure Drops

First and second stage pressure drops should be maintained between 7 and 10 in. W.C. to achieve good liquid pickup while avoiding excessively high or low total pressure drops. Pressure drops close to 7 in. W.C. should be selected when operating with the new generator to minimize power consumption. When older generators are being operated, pressure drops near 10 in. W.C. may be needed to reduce particulate emissions to acceptable levels if combustion problems persist.

Table 9.5 summarizes the recommended stoichiometries, gas rates, pressure drops and slurry pumping rates necessary to achieve optimum performance in the R-C/Bahco system at RAFB with the present particulate and SO_2 emissions requirements. The recommendations made above with regard to minimizing operating costs should be implemented in conjunction with the recommended operating conditions listed below.

TABLE 9.5 SUMMARY OF RECOMMENDED OPERATING CONDITIONS

Reagent	Limestone	Lime
Stoichiometry	0.75	0.7
Slurry rate to scrubber	2200-2400 gpm	2200-2400 gpm
Flue gas rates	35-55,000 scfm	35-55,000 scfm
First stage ΔP	7-10 in. W.C.	7-10 in. W.C.

Note: The stoichiometries listed in this table are for 3.5% sulfur, 11,500 Btu/lb coal. Adjustments to accommodate other coal types used at RAFB are described in the system operating manual.

APPENDIX A

CONVERSION FACTORS: BRITISH TO SI UNITS

To Convert From	To	Multiply by
LENGTH		
inch(in)	meter(m)	2.540×10^{-2}
foot(ft)	meter(m)	0.3048
AREA		
inch^2(in^2)	meter^2(m^2)	6.452×10^{-4}
foot^2(ft^2)	meter^2(m2)	9.290×10^{-2}
VOLUME		
inch^3(in^3)	meter^3(m^3)	1.639×10^{-5}
foot^3(ft^3)	meter^3(m^3)	2.832×10^{-2}
foot^3(ft^3)	liter (l)	28.32
gallon(gal)	meter^3(m^3)	3.785×10^{-3}
gallon(gal)	liter(l)	3.785
MASS		
ounce(oz)	kilogram(kg)	2.835×10^{-2}
pound(lb)	gram(g)	453.6
pound(lb)	kilogram(kg)	0.4536
grain(gr)	gram(g)	6.480×10^{-2}
Ton(T)	kilogram(kg)	907.2
PRESSURE		
inches W.C.(in w.c.)	kilopascal (kPa)	0.2488
pounds/inch^2(psi)	kilopascal (kPa)	6.895
TEMPERATURE		
degree Fahrenheit(°F)	degree centrigrade(°C)	$tc = (t_f - 32)\frac{5}{9}$
degree Rankin(°R)	degree Kelvin(°K)	0.5555
ENERGY		
British Thermal Unit (Btu)	joule(J)	1055.
British Thermal Unit (Btu)	kilojoule(kJ)	1.055

POWER

British Thermal Unit/hour (Btu/hr)	watt(w)	0.2931
British Thermal Unit/hour (Btu/hr)	kilowatt(kw)	$2.931x10^{-4}$
British Thermal Unit/horsepower(hp)	kilowatt(kw)	0.7457

DENSITY

pound/foot^3(lb/ft^3)	kilogram/meter^3 (kg/m^3)	16.02
pounds/gallon(lb/gal)	kilogram/meter^3 (kg/m^3)	119.8

VISCOSITY

pound foot second/foot^2 (lb. ft/sec ft^2)	pascal-second (Pas)	47.89

MISCELLANEOUS

cubic feet/minute(CFM)	meter^3/hour (m^3/hr)	1.699
gallons/1000 ft^3 (gal/M	liter/meter^3 (l/m^3)	0.1337
gallon/minute (gal/min)	liter/minute (l/min)	3.785
grains/standard cubic foot (gr/SCF)	grams/normal meter^3 (g/nm^3)	2.288
feet/second (ft/sec)	meter/second (m/sec)	0.3048
pounds/1,000,000 BTU (lb/MM Btu)	grams/kilojoule (g/kJ)	429.9
British Thermal Units/pound (Btu/lb)	kilojoule/kilogram (kJ/kg)	2.326

APPENDIX B

ANALYTICAL AND TESTING METHODS

B-1 Thermogravimetric Analysis

B-2 Analytical Procedure for SO_2 Wet Tests

B-3 Procedure for Preparing Leachate Samples

B-4 Analytical Methods

APPENDIX B-1

THERMOGRAVIMETRIC ANALYSIS OF SOLIDS FROM BAHCO SCRUBBING PROCESS

General Procedure:

All analyses performed on lime-based scrubbing solids from the Bahco SO_2 Gas Removal Process at Rickenbacker Air Force Base utilized the specific technique of thermogravimetric analysis (TGA). This technique involved heating a prepared sample of solid phase material at a specific rate over a predetermined temperature range and observing the weight change which results from solid state reaction occurring at some characteristic temperature.

After in-laboratory treatment, which includes drying at 35°C for 24 hours,breaking up of the dried solids and riffling as many times as needed to obtain a representative sample of about 2.5 gms.; the prepared solid phase sample is then subjected to analysis on the thermobalance over a preprogrammed temperature range, (ambient to 980°C) at a specific heating rate (80°C per minute). The resulting thermogram will exhibit, in a general case, associated weight losses of 2 waters of hydration from $CaSO_4.2H_2O$(130-200°C), 1/2 water of hydration from $CaSO_3 \cdot 1/2H_2O$(400-450°C), dehydration of $Ca(OH)_2$ (575-625°C), loss on ignition from combustibles (700-750°C) and finally evolution of CO_2 from $CaCO_3$ (800-900°C). Measuring these losses and back calculating each for the particular constituent results in a total analysis of the solids, with the exception of any inert material, which would require separate testing.

In addition to the various calcium compounds which were determined by TGA, it also became necessary to determine the concentration of $MgCO_3$ present in the solid phase during the limestone phase of the test program. Since the limestone used in this phase of the study was dolomitic, the presence of $MgCO_3$ was noticed during initial thermogravimetric testing. To effectively separate the weight losses of CO_2 from $MgCO_3$, and the weight loss from the ignition of combustibles, which overlap at 650°C, it was necessary to reanalyze these samples in a nitrogen environment where combustion would not take place. The resulting weight loss in percent was then back calculated in the same manner as previously stated.

To insure the data obtained from TGA analyses produced a high degree of accuracy, an alternate wet chemical method was employed as a check. This wet test procedure uses the same prepared sample which is reacted in an absorption train assembly using concentrated hydrochloric acid to digest the sample. As the sample digests in the acid medium, CO_2 and SO_2 are evolved and forced through the train. The evolved CO_2 and SO_2 gases are passed through a small gas washing bottle filled with a 3% hydrogen peroxide solution, which traps any SO_2 forming H_2SO_4. The CO_2 gas also passes through the peroxide trap, into a series of acid and moisture traps to a preweighed Miller bulb containing 20 mesh Ascarite, which will absorb the CO_2.

After the digestion has been completed, the reaction flask solution is tested for insolubles, calcium content by EDTA titration (also magnesium content if applicable) and total sulfate by gravimetric means. The solution in the peroxide trap is titrated for SO_2 using a $BaCl_2$ titrant and Thorin as an indicator. The Miller bulb is weighed to determine the weight of CO_2 absorption. From data obtained from these tests we are able to perform a complete analysis of all the constituents previously mentioned. Data obtained by this procedure match TGA results quite closely in all samples tested.

In addition to the use of wet chemical methods to verify TGA data, the use of laboratory prepared samples using reagent grade chemicals similar to those to be determined were also tested by thermal means. Various ratios of $CaSO_4 \cdot 2H_2O$ to $CaSO_3 \cdot 1/2H_2O$ with amounts of $CaCO_3$ and $MgCO_3$ were analyzed by TGA. The data obtained from these TGA analyses also yielded results which correlated closely to calculated percentages in the sample formulations.

Use of a thermogravimetric balance for lime or limestone based solids analysis is a rapid, reliable method for the determination of $CaSO_4 \cdot 2H_2O$, $CaSO_3 \cdot 1/2H_2O$, $Ca(OH)_2$, $MgCO_3$ and $CaCO_3$. The use of this instrument with occasional wet chemical methods produces data which is highly accurate and in substantially less time than comparable wet chemical analyses.

APPENDIX B-2

ANALYTICAL PROCEDURE FOR SO_2 WET TESTS

This method for determining the SO_2 content of gas streams is only approximate and should be used only as a semi-quantitative check on SO_2 concentrations.

No temperature or pressure corrections have been incorporated, and the method should not be used below 100 ppm.

Apparatus:

1) 250 ml impinger with an open glass dip tube.
2) A dry test meter.
3) A source of vacuum.
4) 25 ml pipette.
5) Vacuum tubing.
6) Hose clamp.

Reagents:

1) 3% Hydrogen Peroxide
2) 0.1N NaOH or 0.01 N NaOH
3) Methyl/Orange-Xylene Cyanol indicator

Procedure:

Inlet Samples (i.e., 500 + ppm SO_2) pipette 25 ml of 0.1 N NaOH into the 250 ml impinger, add 50 ml of 3% hydrogen peroxide. Add approximately 25 ml of deionized water. Add several drops of Methyl/Orange-Xylene Cyanol indicator.

Draw the gas sample through the impinger at 0.1 to 0.2 $ft.^3/min$. Record the gas meter reading when the indicator turns from green to purple.

Outlet Samples (100 to 600 ppm SO_2) substitute 0.01 normal NaOH for the 0.1 normal NaOH in the above procedure. Follow the same procedure as above.

The following equation can be used to calculate the SO_2 concentration:

$$SO_2 \text{ ppm} = \frac{10{,}000 \text{ X (NaOH Normality)}}{\text{Meter Volume ft.}^3}$$

Note: Add the indicator within 15 minutes of running the test. If the indicator is added at an earlier time, it may be destroyed by the hydrogen peroxide in the impinger.

APPENDIX B-3

GENERAL PROCEDURE FOR PREPARING A LEACHATE OF A SOLID PROMULGATED BY THE INDIANA STATE BOARD OF HEALTH, SOLID WASTE MANAGEMENT SECTION 9-13-74.

1. Weigh some convenient amount of sample (10-20 gm) into a tared dish, dry at 103° C for one hour; cool, reweigh to determine the amount of moisture in the sample.

2. Place the dried sample in a flask, add distilled water or rainwater (500-1000 ml), and place on a magnetic stirrer for two (2) hours (or some other period that may be specified by the engineer who submitted the sample).

3. Filter the sample, then dry and weigh the residue to determine the percentage of insoluble material.

4. Retain the leachate (filtrate) in a capped bottle, and make the determinations for all parameters using this solution.

5. Calculate all results on a dry basis.

6. Record all steps, times, weights, etc. throughout the entire process.

7. This type of sample should have a high priority in the order of analysis.

APPENDIX B-4

ANALYTICAL METHODS

Listed below are various physical and analytical methods which were employed in testing samples from the BAHCO GAS Cleaning Project at Rickenbacker Air Force Base:

Particle Size (Sub-Sieve) - BAHCO micro-particle classifier as per ASTM procedures

Particle Size (Sieve) - U.S. Standard Sieves as per ASTM procedures

Specific Gravity Determination - Use of calibrated cement pycrometer and ASTM procedure

Bulk Density - Use of ASTM procedure for compacted bulk density

Thermo-gravimetric Analysis - Used in analyzing solids from scrubbing process; limestone and lime samples for $CaSO_4 \cdot 2H_2O$, $CaSO_3 \cdot \frac{1}{2}H_2O$, $Ca(OH)_2$, $MgCO_3$, $CaCO_3$ and loss on ignition (see detailed description supra.)

Total Sulfate Analysis - Standard gravimetric procedure for total sulfate measurements. Ref. Scott's Standard Methods of Chemical Analysis

Total Calcium Content - Research-Cottrell analytical procedure using EDTA titrant and Hydroxy Napthol-Blue indicator

Total Magnesium Content - Research-Cottrell analytical procedure using EDTA titrant and Erichrome Black "T" indicator

Alkalinity Determination - Used Research-Cottrell analytical methods for determining alkalinity present in lime and slurry samples

Chloride Determination - Conducted as per Agentometric procedure outlined in Standard Methods of Water and Wastewater Analysis

Coal Analysis - Methods as per those specified by U.S. Bureau of Mines publication PB-209-036. *Instrumentation used for the various tests are as follows:

- Percent Sulfur in coal - Leco Sulfur Analyzer
- B.T.U. Values - Parr Calorimeter
- Percent Carbon, Hydrogen, Nitrogen - Perkin Elmer 240-Analyzer

Trace Elemental Analysis - Methods used to determine concentrations of Hg, Cd, Pb and Cr were derived from Varian Techtron publication 85-100224-00 and Jarrell Ash reference material dealing with flameless Atomic Absorption Spectroscopy. Methods from these sources were employed in conjunction with a Model 850 Jarrell Ash Atomic Absorption Spectrophotometer

APPENDIX C

MATERIAL BALANCE TEST DATA

C-1 Coal Analyses

C-2 Lime Analyses

C-3 Lime/SO_2 Stoichiometry, Lime Utilization and SO_2 Emission Rates

C-4 Slurry Chemical Analyses

C-5 A Procedure for Determining Gas Flow Rate and the Lime Feeder Calibration Curve

TABLE C-1 MATERIAL BALANCE COAL ANALYSES

1976 DATE	CARBON	MOISTURE	SULFUR ORGANIC	SULFUR PYRITIC	SULFATE	ASH	BTU/Lb*
3-21	67.17	7.50	1.83	1.36	0.26	6.88	12,265
3-30	67.29	7.97	1.74	1.19	0.31	6.64	12,164
4-29	65.95	8.90	1.73	1.02	0.39	7.13	11,957
5-1	63.52	11.80	1.68	1.23	0.38	6.84	11,598
5-19	65.34	6.10	1.78	0.70	0.77	8.65	11,748
5-20	62.91	8.80	1.70	1.35	0.66	8.67	11,359
5-26	62.21	8.10	1.31	0.69	0.64	10.86	11,167
5-27	61.04	9.58	0.95	0.66	0.40	11.70	10,898

* As-Fired

TABLE C-2 MATERIAL BALANCE LIME ANALYSES

1976 DATE	TIME	% ALKALINITY AS CaO	DATE	TIME	% ALKALINITY AS CaO
3-30	1500	88.26	5-26	1300	76.38
5-19	1045	89.82	5-26	1500	76.94
5-20	1030	82.77	5-27	0900	73.33
5-21	1100	84.34	5-27	1300	81.87
5-26	0900	74.14	5-28	0900	79.63
5-26	1100	74.70	5-28	1100	73.86

TABLE C-3

MATERIAL BALANCE TESTS RESULTS
LIME STOICHIOMETRY UTILIZATION AND SO_2 EMISSIONS

1976 Date	Time	Outlet SO_2 ppm	SO_2 Removal Efficiency %	Stoichiometry	SO_2 Emissions, lbs/10^6 BTU	Lime Utilization	Lime Feed Rate, lbs./hr.
3-30	1045	156	87.59	0.876	0.615	100.0	440
5-19	0900	24	94.39	0.955	0.289	99.4	611
5-26	0900	5	98.98	1.096	0.045	89.8	146
5-26	1300	8	98.23	1.086	0.078	90.5	164
5-26	1500	8	97.85	1.072	0.095	91.2	174
5-27	1300	5	98.25	1.043	0.060	94.4	182
5-27	1500	5	98.23	1.030	0.061	94.8	194

TABLE C-4

MATERIAL BALANCE CHEMICAL ANALYSES (WT.%)

1976 Date	Time	Location*	% Acid Insolubles	%$CaSO_4\cdot 2H_2O$	%$CaSO_3\cdot 0.5H_2O$	%$Ca(OH)_2$	%$CaCO_3$	% Ignition Loss
3-18	0930	D	4.87	10.63	80.83	0	0.14	0.73
3-18	0945	S	5.03	9.87	80.18	0	0.12	0.80
3-29	1630	S	2.44	78.13	15.06	0	0	0.32
3-29	1630	D	3.32	70.60	24.02	0	0	0.42
3-30	1600	S	3.15	56.39	37.71	0	0	0.75
3-30	1600	D	3.48	49.70	46.24	0	0	0.74
3-31	1500	S	3.38	59.16	35.85	0	0	0.25
3-31	1500	D	3.34	60.35	35.70	0	0	0.38
4-8	1530	D	8.69	27.95	63.09	0	0	1.50
5-19	0945	D	7.91	50.89	40.86	0	0	--
5-19	0945	S	2.20	50.17	46.89	0	0.80	--
5-19	1700	D	1.80	35.12	56.64	0	1.02	--
5-19	1700	S	2.17	34.88	58.07	0	1.14	--
5-20	0845	S	1.12	23.89	70.26	0	1.12	--
5-20	0915	Pond	1.50	37.03	55.20	0	2.84	--
5-20	1015	D	1.82	29.63	64.52	0	1.14	--
5-21	0930	S	4.11	46.35	47.32	0	0.80	--
5-21	1000	D	8.83	40.86	50.18	0	1.25	--
5-21	1315	S	2.52	51.37	40.50	0	0.84	--
5-25	1300	D	3.17	47.31	42.30	0	10.46	--
5-25	1300	S	3.24	46.11	40.15	0	10.23	--
5-25	1500	D	3.42	45.63	40.15	0	9.63	--
5-25	1500	S	3.47	45.87	38.00	0	9.55	--
5-26	0900	D	4.37	34.88	53.06	0	7.28	--
5-26	0900	S	3.76	34.88	51.62	0	6.48	--
5-26	1100	Pond	3.50	70.48	24.37	0	5.12	--
5-26	1100	S	4.23	32.02	55.92	0	6.14	--

* D - Dissolving Tank
S - First Stage Seal Tank

TABLE C-4

MATERIAL BALANCE CHEMICAL ANALYSES (WT.%) (CONT.)

1976 Date	Time	Location*	% Acid Insolubles	%$CaSO_4 \cdot 2H_2O$	%$CaSO_3 \cdot 0.5H_2O$	%$Ca(OH)_2$	%$CaCO_3$	% Ignition Loss
5-26	1100	D	2.29	31.78	55.92	0	6.60	--
5-26	1300	Pond	3.36	70.96	24.37	0	2.96	--
5-26	1300	D	4.56	29.63	57.35	0	6.37	--
5-26	1300	S	4.70	29.15	57.35	0	6.48	--
5-26	1500	D	4.31	27.48	63.80	0	6.37	--
5-26	1500	S	5.25	27.71	60.22	0	6.03	--
5-27	0900	D	4.89	22.46	65.24	0	4.89	--
5-27	0900	Pond	3.90	49.93	40.86	0	2.73	--
5-27	1300	D	5.27	23.68	64.52	0	3.64	--
5-27	1300	S	5.74	23.68	63.80	0	3.87	--
5-27	1500	D	5.67	25.09	62.37	0	3.89	--
5-27	1500	S	5.67	25.09	62.37	0	3.07	--
5-28	0900	Pond	2.78	61.40	29.39	0	2.62	--
5-28	0900	D	5.68	28.43	61.65	0	5.91	--
5-28	0900	S	5.75	24.13	62.37	0	5.75	--
5-28	1100	D	4.20	26.28	61.87	0	5.12	--
5-28	1100	S	4.35	24.33	63.97	0	5.23	--

* D - Dissolving Tank
S - First Stage Seal Tank

APPENDIX C-5

GAS FLOW ESTIMATION FROM FAN AND MOTOR PERFORMANCE CURVES AND LIME FEEDER CALIBRATION

The following figures, A for fan motor current vs. horsepower output, B, fan horsepower vs. flow, were used extensively during the test program to determine the scrubber gas flow rate.

Fan motor current, pressure differential and gas temperature measurements were routinely taken. Gas flow was determined as follows: First determine the motor horsepower from Figure A, based on the observed fan motor current draw. Then determine the gas flow rate from Figure B, based on the motor horsepower, gas temperature and pressure differential observed.

Figure C illustrates the calibration of the lime feeder.

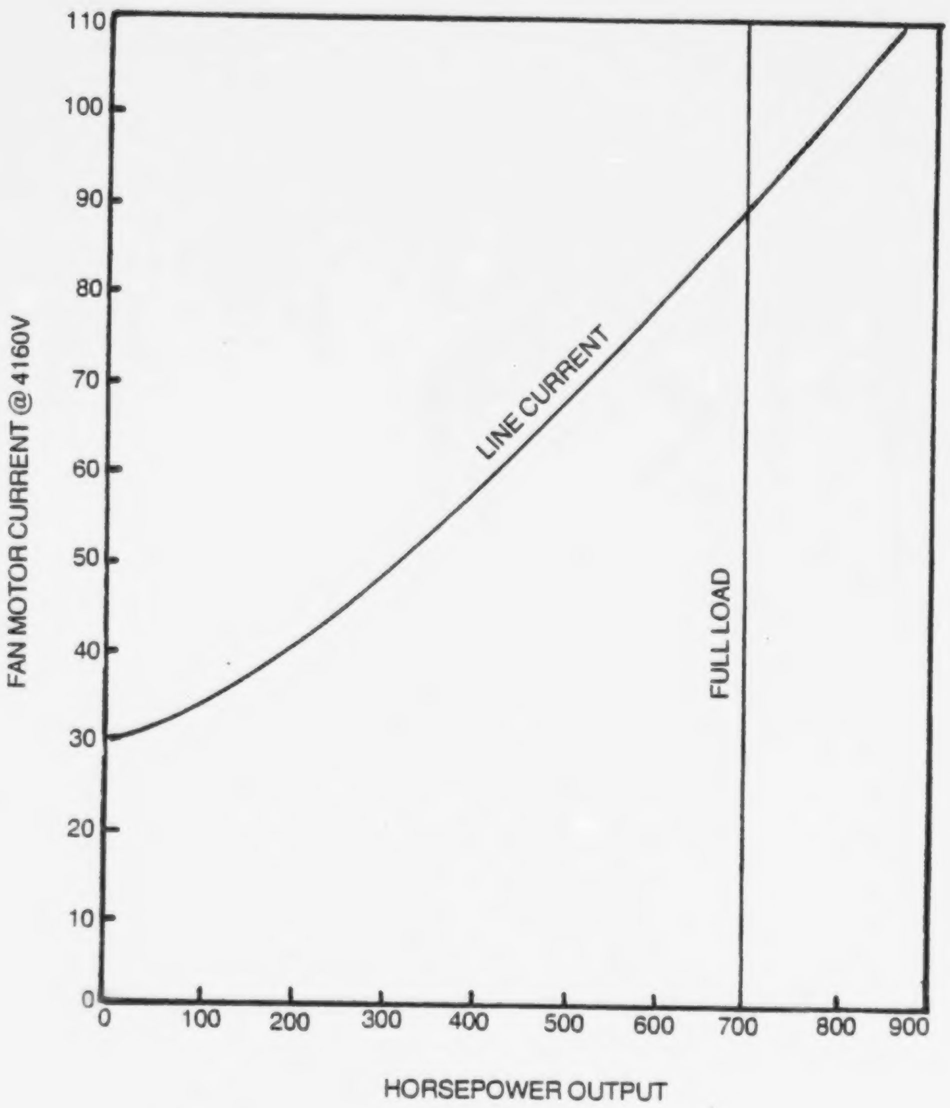

FIGURE A: Fan motor current vs. horsepower.

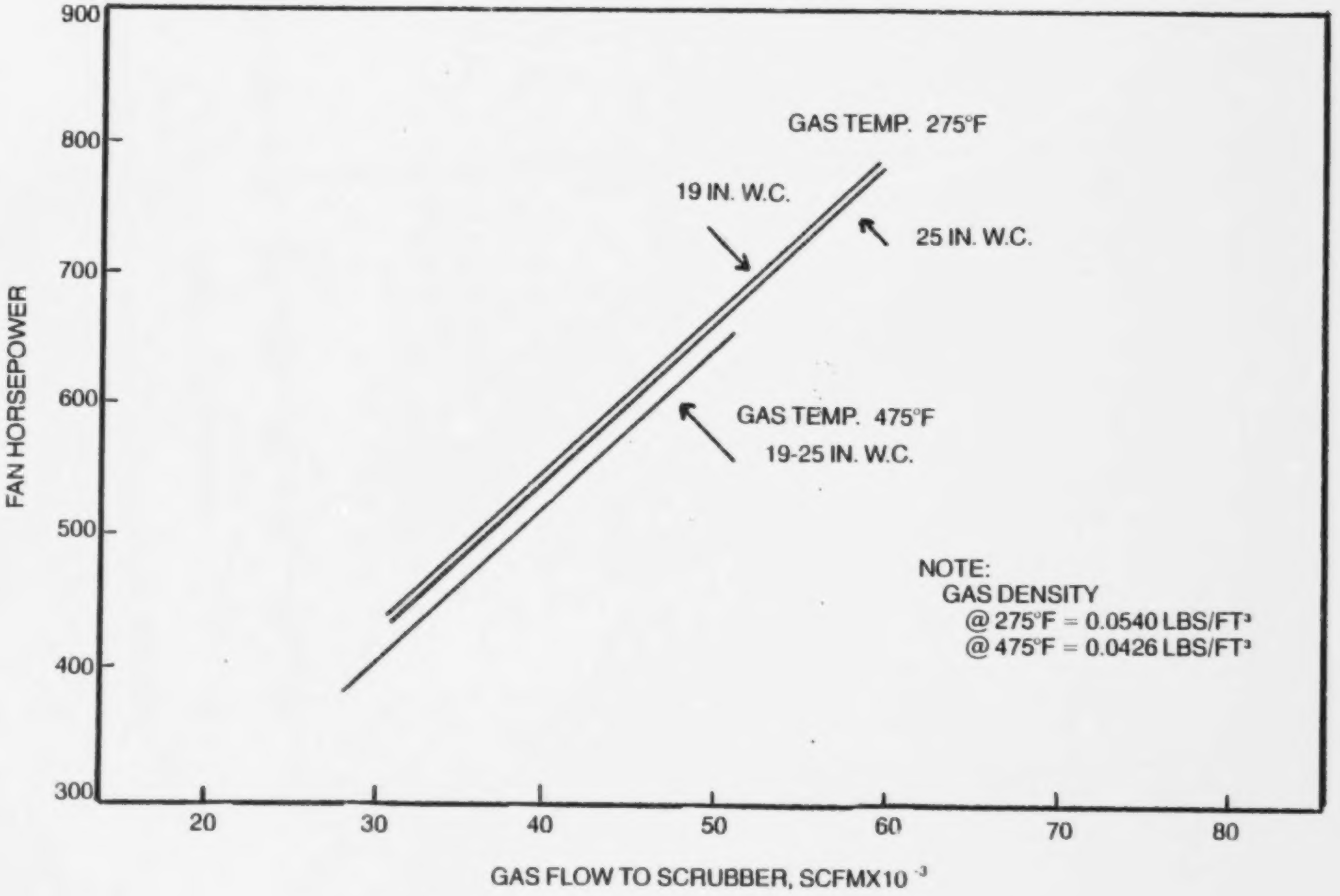

FIGURE B: Fan horsepower and gas flow rates.

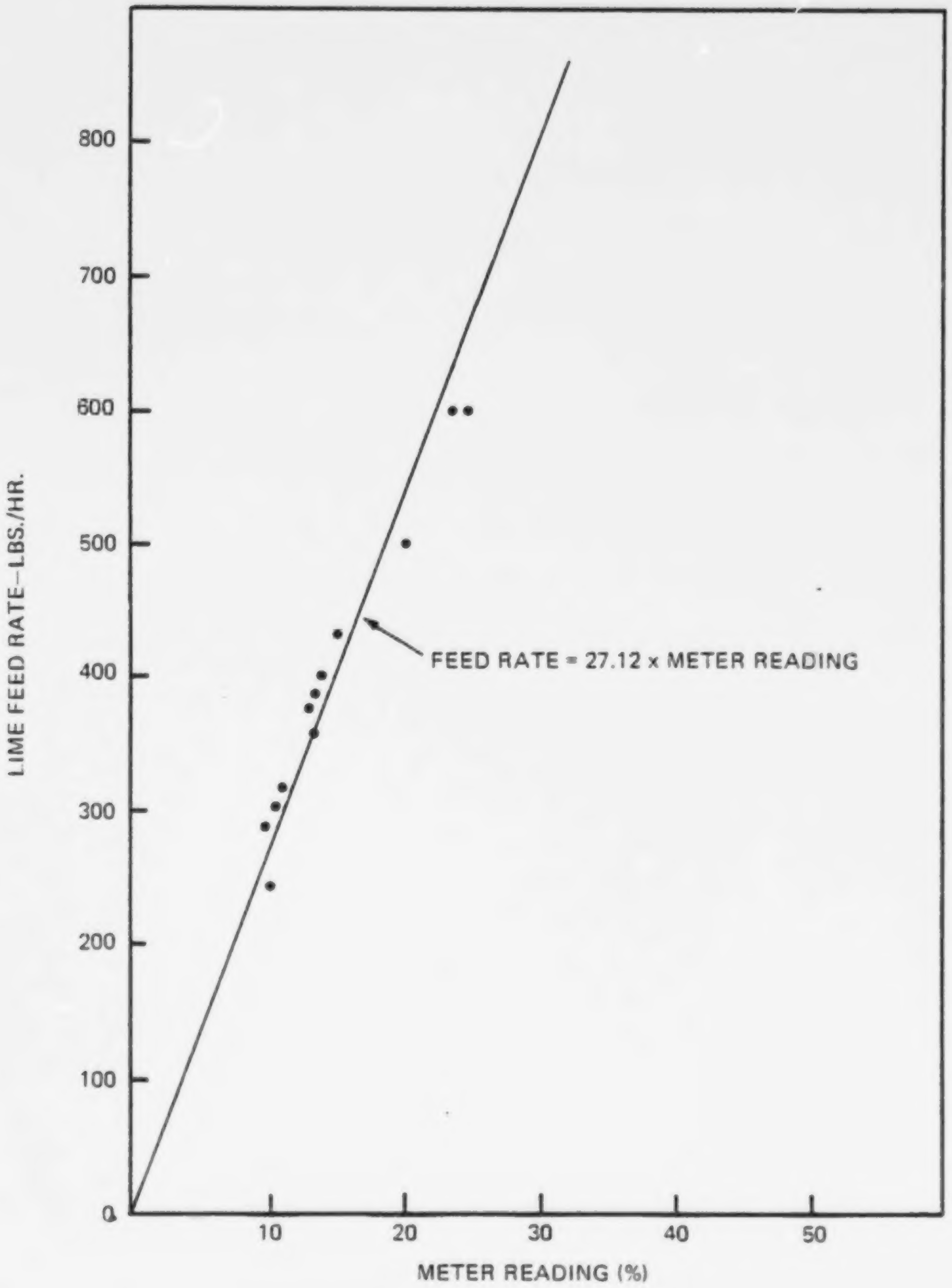

FIGURE C : Lime Feeder Calibration Curve.

APPENDIX D

LIME TEST DATA

D-1 Lime/SO_2 Stoichiometry, Lime Utilization and SO_2 Emission Rates
D-2 Lime Test pH Data
D-3 Slurry Chemical Analyses
D-4 Scrubber Operating Data
D-5 Inlet and Outlet SO_2 Concentration Data
D-6 Numerical Results of the Significant Effect Analysis

TABLE D-1 LIME STATISTICAL TESTS - STOICHIOMETRY AND SO_2 EMISSIONS

TEST NO.	AVERAGE SO_2 ppm INLET	OUTLET	COAL FIRING RATE lbs/hr	COAL HEATING VALUE, Btu/lb	AVERAGE LIME/SO_2 STOICHIOMETRY	AVERAGE LIME UTILIZATION	AVERAGE SO_2 EMISSIONS lbs/10^6Btu
1	1110	104	14,098	11,012	0.936	95.4	0.342
2R *	1500	550	13,213	11,143	0.596	100.0	1.566
3	1000	28	14,994	11,233	1.003	96.7	0.072
4	992	40	13,991	11,861	0.985	96.8	0.143
5R	1140	365	13,361	11,143	0.654	98.7	2.075
6	1100	81	13,214	10,877	0.928	99.7	0.237
7R	1350	494	13,368	10,687	0.598	100.0	1.497
8	1275	742	13,229	11,143	0.360	100.0	3.019
9	910	58	12,712	11,861	0.967	95.8	0.239
10	1075	41	13,229	11,585	0.991	96.5	0.135
11	1150	70	14,627	11,585	0.976	95.9	0.217
12	842	40	15,522	10,958	0.994	95.1	0.150
13	940	174	10,789	10,958	0.805	98.0	0.903
14R	1200	546	14,983	10,664	0.545	100.0	1.424
15	1500	25	16,639	11,656	1.061	92.5	0.058
16	1095	340	10,448	10,664	0.658	100.0	1.944
17	1000	115	15,878	10,819	0.917	97.5	0.422
18	1155	14	20,313	11,261	1.080	91.2	0.028
19	348	348	12,539	10,819	0.667	95.1	1.052
20	370	370	8,954	11,107	0.604	95.6	1.803
21	1075	172	10,430	11,145	0.855	96.2	0.737

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* The "R" designation indicates a repeat test run.

TABLE D-2 AVERAGE pH DATA FOR LIME STATISTICAL TESTS

		DROP COLLECTOR pH		LEVEL TANK pH	
TEST NO.	DISSOLVER pH	FIRST STAGE	SECOND STAGE	FIRST STAGE	SECOND STAGE
1	7.4	6.2	5.6	-	8.0
2R*	6.1	5.3	5.0	-	5.8
3	8.6	6.5	7.6	-	8.5
4	-	5.8	5.6	-	8.1
5R	6.4	5.4	5.2	-	6.2
6	9.4	7.5	8.4	-	9.3
7R	6.3	5.4	5.1	-	5.9
8	-	-	-	-	-
9	-	7.8	8.0	-	8.3
10	7.5	5.8	5.5	7.0	7.9
11	7.1	5.7	5.4	7.0	7.1
12	8.9	8.0	8.2	-	9.3
13	5.5	5.0	4.8	5.1	5.3
14R	5.0	4.3	4.4	-	5.2
15	-	7.0	8.0	-	-
16	7.6	5.0	5.0	7.9	7.7
17	9.6	7.1	8.0	-	8.5
18	8.2	6.2	7.2	8.6	8.7
19	9.6	5.6	5.9	-	9.3
20	7.4	4.5	-	4.9	5.9
21	8.2	5.6	6.0	-	8.1

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* The "R" designation indicates a repeat test run.

TABLE D-3 LIME TESTS, CHEMICAL ANALYSES (WT.%) AND UTILIZATION

1976 Date	Time	Location*	Test	% Acid Insolubles	%$CaSO_4 \cdot 2H_2O$	% $CaSO_3 \cdot 0.5H_2O$	% $Ca(OH)_2$	% $CaCO_3$	% Ignition Loss	% Lime Utilization
12-13	1930	D	15	4.49	29.29	60.65	1.58	2.55	4.73	93.18
12-13	1930	S	15	3.93	36.79	53.91	1.91	2.25	5.67	92.90
12-13	2200	D	15	3.67	28.43	57.78	1.58	3.41	5.40	91.71
12-13	2200	S	15	4.52	26.90	61.65	1.19	3.66	5.53	92.33
12-14	1800	D	7	4.71	35.60	55.92	0.82	2.73	4.83	94.35
12-14	1800	S	7	4.83	39.18	54.48	0.62	2.50	4.66	95.12
12-14	1945	D	7	4.45	32.97	57.35	1.03	3.30	4.66	93.13
12-14	1945	S	7	4.87	33.21	60.22	0.62	1.41	5.01	96.71
12-15	1200	D	9	4.25	28.05	66.10	2.06	0.80	5.33	94.96
12-15	1200	S	9	4.32	27.91	66.82	1.73	0.45	6.12	96.06
12-15	1300	D	9	4.14	28.62	66.67	0.95	1.29	5.83	96.37
12-15	1300	S	9	4.33	27.67	65.67	0.95	1.64	5.10	95.82
12-15	1715	D	4	3.90	23.94	71.55	1.03	1.41	5.32	96.12
12-15	1715	S	4	4.24	23.99	70.54	0.41	2.30	4.92	96.01
12-15	2030	D	4	4.62	25.18	67.68	0	1.48	4.36	97.84
12-15	2030	S	4	4.35	26.04	67.53	0.41	1.25	5.26	97.40
12-15	2130	D	5	4.26	28.72	64.23	1.03	0.91	3.96	96.65
12-15	2130	S	5	4.31	31.54	61.51	1.03	0.73	5.00	96.89
12-15	2230	D	5	4.37	29.15	61.22	1.03	0.91	3.84	96.55
12-15	2230	S	5	4.32	31.63	60.79	1.03	0.91	4.16	96.61
12-16	1630	D	1	4.86	21.50	73.55	1.77	1.14	5.30	95.16
12-16	1630	S	1	4.50	22.12	67.39	1.77	1.09	4.80	94.92
12-16	1815	D	1	4.74	26.19	66.96	1.44	1.07	4.43	95.70
12-16	1815	S	1	4.82	27.48	65.95	1.23	1.18	4.44	95.41
12-17	1500	D	2	4.79	36.55	56.35	1.11	1.09	3.54	96.16
12-17	1500	S	2	4.32	43.96	51.87	1.07	0.64	3.61	96.93
12-17	1645	D	2	4.69	39.90	55.92	1.27	0.84	4.04	96.30
12-17	1645	S	2	4.37	46.59	47.03	1.48	0.50	3.68	96.21

* D - Dissolver tank
S - First stage drop collector

TABLE D-3 LIME TESTS, CHEMICAL ANALYSES (WT.%) AND UTILIZATION (CONT.)

1976 Date	Time	Location*	Test	% Acid Insolubles	%$CaSO_4\cdot$ $2H_2O$	% $CaSO_3\cdot$ $0.5H_2O$	% $Ca(OH)_2$	% $CaCO_3$	% Ignition Loss	% Lime Utilization
12-17	2000	D	3	386	47.59	45.02	1.48	0.50	3.43	96.16
12-17	2000	S	3	4.03	45.39	48.32	1.11	0.50	3.84	96.96
12-17	2045	D	3	3.76	41.81	51.04	1.11	0.39	4.25	97.13
12-17	2045	S	3	4.09	41.57	51.62	1.28	0.45	3.93	96.72
12-18	1500	D	10	4.35	19.11	76.71	1.78	0.98	5.99	96.30
12-18	1500	S	10	4.48	18.49	74.84	0.99	0.84	5.72	96.93
12-18	1700	D	10	4.74	19.21	74.84	1.52	0.61	6.26	96.29
12-18	1700	S	10	4.79	19.11	74.99	1.44	0.56	5.67	96.51
12-18	2030	D	11	4.62	17.97	77.57	1.44	0.56	6.03	96.57
12-18	2030	S	11	4.65	19.02	74.99	1.44	1.02	5.39	95.89
12-18	2215	D	11	4.35	23.03	71.40	1.85	0.56	5.71	95.74
12-18	2215	S	11	4.36	24.90	68.82	2.06	0.45	5.64	95.45
12-19	1800	D	12	2.79	17.20	74.56	1.03	2.23	6.47	94.93
12-19	1800	S	12	3.18	16.15	78.14	0.66	2.20	6.37	95.77
12-19	2000	D	12	2.90	16.19	77.20	0.66	2.66	6.19	95.12
12-19	2000	S	12	3.14	13.33	80.87	0.66	3.05	6.68	94.70
12-19	2300	D	13	4.45	13.14	81.87	0	1.82	6.10	97.50
12-19	2300	S	13	5.14	20.31	72.69	0	1.43	5.37	97.95
12-19	2350	D	13	4.95	20.31	72.69	0.41	1.02	5.39	97.74
12-19	2350	S	13	5.18	22.60	70.11	0.41	0.34	5.01	98.69
12-20	1715	D	14	5.94	90.69	1.58	0	0	1.80	100.00
12-20	1715	S	14	3.33	69.91	22.08	2.30	0.23	2.20	94.54
12-20	1845	D	14	4.87	89.60	3.30	0	0	1.50	100.00
12-20	1845	S	14	2.65	94.37	1.43	0	0	1.41	100.00
12-20	2200	D	18	4.45	63.27	27.39	2.55	1.71	2.72	91.84
12-20	2200	S	18	3.92	77.70	16.20	3.54	0.91	1.83	91.02
12-20	2345	D	18	4.28	72.01	19.07	3.99	1.14	1.14	89.66
12-20	2345	S	18	3.23	75.26	17.78	2.63	1.16	1.76	92.43

* D - Dissolver tank
S - First stage drop collector

TABLE D-3 LIME TESTS, CHEMICAL ANALYSES (WT.%) AND UTILIZATION (CONT.)

1977 Date	Time	Location*	Test	% Acid Insolubles	%$CaSO_4\cdot 2H_2O$	% $CaSO_3\cdot 0.5H_2O$	% $Ca(OH)_2$	% $CaCO_3$	% Ignition Loss	% Lime Utilization
2-10	2000	D	20	4.42	60.49	33.84	0.82	1.34	2.61	96.17
2-10	2000	S	20	4.35	63.07	29.82	1.89	1.66	2.36	93.42
2-10	2100	D	20	4.63	56.58	37.71	0.62	1.55	2.83	96.30
2-10	2100	S	20	4.96	56.24	34.98	0.70	1.16	2.42	96.60
2-13	1330	D	14R	4.27	89.60	3.58	0	0	1.19	100.00
2-13	1330	S	14R	8.96	85.10	6.45	0	0	3.15	100.00
2-13	1430	D	14R	6.59	89.60	3.58	0	0	2.82	100.00
2-13	1430	S	14R	10.85	89.16	2.58	0	0	3.06	100.00
2-13	1845	D	16	6.74	82.67	8.89		0	2.67	100.00
2-13	1845	S	16	9.82	80.95	9.03	0	0	2.43	100.00
2-13	1945	D	16	6.93	79.42	12.62	0	0	3.03	100.00
2-13	1945	S	16	8.18	79.18	12.47	0	0	3.79	100.00
2-14	1430	D	21	5.39	46.35	48.03	0	0	4.62	100.00
2-14	1430	S	21	5.87	56.15	35.70	0.98	4.09	2.60	91.76
2-14	1515	D	21	5.10	49.41	42.87	1.69	0.45	2.99	95.77
2-14	1515	S	21	5.16	51.13	39.86	1.15	0.22	2.47	97.16
2-15	1300	D	19	4.40	30.92	64.09	2.47	1.11	4.16	93.83
2-15	1300	S	19	4.92	43.15	48.61	0.98	2.84	2.97	90.22
2-15	1400	D	19	4.26	31.06	63.66	1.03	0.34	5.23	97.50
2-15	1400	S	19	4.76	37.13	55.97	0.41	0.34	3.11	98.64
2-15	1930	D	17	3.71	22.98	70.97	0.90	0.23	5.16	97.93
2-15	1930	S	17	4.53	20.11	71.40	0.62	0.80	3.57	97.62
2-15	2030	D	17	3.84	21.79	68.39	1.02	0.73	4.11	96.89
2-15	2030	S	17	4.35	22.65	68.39	0.72	0.57	3.45	97.72
2-16	1800	D	6	4.51	23.18	78.09	0	0.19	5.36	99.74
2-16	1800	S	6	4.28	22.50	77.36	0	0.28	5.14	99.62
2-16	1900	D	6	3.99	20.98	77.43	0	0.57	5.29	99.22
2-16	1900	S	6	4.34	21.54	77.00	0	0	5.05	100.00
2-17	1200	D	5R	4.74	6.69	87.75	0	0	3.68	100.00
2-17	1200	S	5R	4.54	7.50	84.59	0	3.98	3.52	94.62

TABLE D-3 LIME TESTS, CHEMICAL ANALYSES (WT.%) AND UTILIZATION (CONT.)

1977 Date	Time	Location	Test	% Acid Insolubles	%$CaSO_4 \cdot 2H_2O$	% $CaCO_3 \cdot 0.5H_2O$	% $Ca(OH)_2$	%$CaCO_3$	Ignition Loss	% Lime Utilization
2-17	1300	D	5R	4.38	5.88	87.61	0	0	3.52	100.00
2-17	1300	S	5R	4.76	7.07	88.90	0	0	3.82	100.00
2-17	1815	D	2R	4.84	9.32	84.88	0	0	3.40	100.00
2-17	1815	S	2R	5.07	9.56	84.88	0	0	3.79	100.00
2-17	1915	D	2R	4.77	8.94	85.31	0	0	3.45	100.00
2-17	1915	S	2R	4.51	9.22	83.73	0	0	3.13	100.00
2-17	2230	D	8	5.54	14.96	76.56	0	0	2.97	100.00
2-17	2230	S	8	4.82	15.60	76.13	0	0	2.42	100.00
2-17	2330	D	8	5.69	14.10	79.58	0	0	3.18	100.00
2-17	2330	S	8	4.63	16.72	78.14	0	0	3.20	100.00
2-18	1145	D	7R	4.44	16.72	78.14	0	0	3.43	100.00
2-18	1145	S	7R	5.25	18.64	74.27	0	0	2.84	100.00
2-18	1230	D	7R	4.61	18.01	75.27	0	0	2.92	100.00
2-18	1230	S	7R	4.52	20.21	74.70	0	0	3.48	100.00

TABLE D-4 SCRUBBER OPERATING DATA LIME TEST

TEST NO.	DATE	SCRUBBER GAS FLOW (acfmx10^3 120°F)	SECOND STAGE SLURRY PUMP RATE (gpm)	SLURRY % SOLIDS	AVERAGE PRESSURE DROP (in.H_2O)			AVERAGE LIQUID PICKUP (gpm)		AVERAGE L/G (gal./10^3 acf	
					TOTAL	FIRST STAGE	SECOND STAGE	FIRST STAGE	SECOND STAGE	FIRST STAGE	SECOND STAGE
1	12-16-76	56.2	2780	10.8	16.0	7.0	9.0	1200	600	21.4	10.7
2R	2-17-76	46.2	2350	14.2	14.0	8.5	5.5	1005	180	21.8	3.9
3	12-17-76	47.6	2130	17.0	16.8	5.0	11.8	525	900	11.0	18.9
4	12-15-76	65.4	3100	16.9	24.0	11.0	13.0	1400	840	21.4	12.8
5R	2-17-76	68.1	1675	13.0	17.6	12.8	4.8	1110	90	16.3	1.3
6	2-16-76	46.3	2500	11.8	21.5	14.5	7.0	1065	330	23.0	7.1
7R	2-18-76	47.7	1700	12.9	18.4	7.6	10.8	735	585	15.4	12.3
8	2-17-76	66.1	3000	14.2	21.8	8.8	13.0	1170	750	17.7	11.3
9	12-15-76	68.6	2320	14.3	19.1	9.6	9.5	1290	960	18.8	14.0
10	12-18-76	55.7	2230	10.5	17.5	9.5	8.0	1050	570	18.9	10.2
11	12-18-76	57.9	2700	8.5	18.0	9.5	8.5	1080	600	18.7	10.4
12	12-19-76	70.2	2800	7.5	16.4	8.0	8.0	1050	600	15.0	8.5
13	12-19-76	67.6	2120	5.2	18.8	7.0	11.8	600	1050	8.9	15.5
14R	2-13-76	45,9	2500	4.9	25.5	12.5	13.0	1080	1065	23.5	23.2
15	12-13-76	49.3	2400	7.8	19.3	12.7	6.6	780	450	15.8	9.1
16	2-13-76	70.2	2230	6.1	19.7	10.5	9.2	1050	300	15.0	4.3
17	2-15-76	64.5	1425	66.7	17.0	6.0	11.0	750	630	11.6	9.8
18	12-20-76	50.4	2400	6.1	25.0	13.0	12.0	1110	1260	22.0	25.0
19	2-15-76	45.2	1475	6.5	9.2	4.2	5.0	390	150	8.6	3.3
20	2-10-76	53.4	2025	10.4	16.0	8.0	8.0	820	300	15.4	5.6
21	2-14-76	54.9	1975	8.1	13.8	6.8	7.0	900	330	16.4	6.0

TABLE D-5 LIME TESTS, SO_2 CONCENTRATION DATA

Test No.	DuPont/ Wet Test	SO_2 Concentration (ppm) Inlet	Outlet	Corrected Outlet	Overall Efficiency (%)
1	D	1110	104	104	89.35
2R	D	1500	---	---	---
	W	---	---	550	59.60
3	D	1000	28	28	96.79
4	D	992	40	40	95.36
5R	D	1140	---	---	---
	W	---	365	365	64.51
6	D	1100	75	81	92.50
7R	D	1350	---	---	---
	W	---	---	494	59.77
8	D	1275	---	---	---
	W	---	---	742	35.98
9	D	910	58	58	92.67
10	D	1075	41	41	95.60
11	D	1150	70	70	93.30
12	D	842	40	40	94.56
13	D	940	174	174	78.83
14R	D	1200	---	---	---
	W	---	546	546	54.50
15	D	1500	25	25	98.17
16	D	1095	---	---	---
	W	---	---	340	65.84
17	D	1000	90	97	89.45
	W	---	115	115	87.49
18	D	1155	20	14	98.67
19	D	1045	---	---	---
	W	---	348	348	63.40
20	D	950	---	---	---
	W	934	370	370	57.78
21	D	1075	---	---	---
	W	---	---	172	82.27

TABLE D-6 NUMERICAL RESULTS OF THE SIGNIFICANT EFFECT ANALYSIS

System Responses	Independent Variables								Minimum Significant Effect (95% Conf. Level)
	Inlet Gas Flow Rate	1st Stage Δ P	2nd Stage Δ P	2nd Stage Slurry Flow Rate	Mill Pump Rate	Stoichiometry	System Volume	Slurry Concent. (% Solids)	
SO_2 Removal Efficiency	-.0149	.0084	-.0423	-.0486	.0559	.3429	.0446	-.0501	0.0996
1st Stage Liquid Pickup	152.5	190.0	17.5	430.0	55.0	25.0	62.5	115.0	172.4
2nd Stage Liquid Pickup	-17.5	-155.0	550.0	115.0	-12.5	192.5	55.0	-152.5	233.6
1st Stage Drop Collector pH	.20	-.275	-.75	-.30	.075	1.825	-.325	.10	0.6
Total Alkalinity in Scrubber Slurry	.0095	-.01885	-.0023	-.0076	.0093	.037	.00043	-.025	0.02167

Note: Independent variables which have an effect at the 95% confidence level on system responses are underlined in this table.

TABLE D-6 NUMERICAL RESULTS OF THE SIGNIFICANT EFFECT ANALYSIS (CONT.)

	Independent Variables								
System Responses	Inlet Gas Flow Rate	1st Stage Δ p	2nd Stage Δ p	2nd Stage Slurry Flow Rate	Mill Pump Rate	Stoichiometry	System Volume	Slurry Concent. (% Solids)	Minimum Significant Effect (95% Conf. Level)
Total Alkalinity in Drop Collector Slurry	-.0057	-.0126	-.0059	-.0099	.0105	.0316	.0056	.018	0.0256
% Sulfate in Scrubber Slurry	-12.09	7.57	9.58	15.9	14.85	-1.59	-5.63	-23.71	28.78
% Sulfate in Drop Collector Slurry	-14.14	5.35	10.09	14.33	-11.77	-2.58	-7.66	-25.71	28.7

APPENDIX E

REAGENT AND COAL DATA

E-1 Coal Properties
E-2 Lime Specifications
E-3 Lime Analyses
E-4 Limestone Specifications
E-5 Limestone Analyses

APPENDIX E-1 COAL PROPERTIES

COAL (Data are reported on an as-fired basis)
Supplier: Peabody Coal Co., Columbus, Ohio
Type: Mixture of Sunny Hill and Broken Arrow mines, New Lexington, Ohio

Analysis:

Sunny Hill Coal	Broken Arrow Coal
6 to 12%, 9.8 av. wt.% moisutre	7 to 12%, 9.2 av. wt.% moisture
11.2 av. wt.% ash	6.2 av. wt.% ash
2.7 av. wt.% sulfur	3.5 av. wt.% sulfur
10,400 to 12,200, Btu/lb 11,080 av.	11,900 to 12,800, Btu/lb 12,200 av.

APPENDIX E-2 LIME SPECIFICATIONS

Source: Black River Mine
Butler, Kentucky

Specifications: Quicklime
$\geq$ 83% CaO

72°F temperature rise in three minutes and slaking reaction complete in ten minutes or less when added to water at a four to one ratio weight.

Particle size not to exceed 3/4 inch.

Should be freshly burned and substantially free of carbonate solids and silicious residue. Amount of such materials (insolubles) not to exceed 5%.

APPENDIX E-3 LIME ANALYSES

Date	Total Alkalinity (as % CaO)	Date	Total Alkalinity (as % CaO)
12-13-76	84.90	2-13-77	96.21
12-14-76	80.86*	2-14-77	96.21
12-15-76	85.90	2-15-77	96.21
12-16-76	74.70*	2-16-77	96.21
12-17-76	75.26*	2-17-77	96.21
12-18-76	75.71*	2-18-77	96.21
12-19-76	75.26*	3-14-77	87.92
12-20-76	75.26*	3-15-77	88.48
2-10-77	95.09	3-16-77	88.48
2-13-77	95.09	3-17-77	88.48

*These samples contained less CaO than required by the reagent specification listed in Appendix E-2.

APPENDIX E-4 LIMESTONE SPECIFICATIONS

Source: Armco Piqua Quarry
Piqua, Ohio

Specifications: YA-stonedust (pulverized limestone)
86% $CaCO_3$
13% $MgCO_3$ quarry specifications

Particle size distribution =

100% through 40 mesh	(375μ)
99.9% through 60 mesh	(250μ)
99.7% through 80 mesh	(177μ)
99% through 100 mesh	(149μ)
85% through 200 mesh	(74 μ)
70% through 30 mesh	(47 μ)

APPENDIX E-5 LIMESTONE ANALYSES

Date	% $CaCO_3$	% $MgCO_3$
5-11-77	89.5	8.6
5-12-77	89.6	8.4
5-16-77	90.4	8.9
5-17-77	86.6	10.4
5-19-77	87.9	9.2
5-20-77	87.2	10.0
5-23-77	86.6	10.7
5-24-77	86.6	9.9
5-25-77	86.4	11.8

APPENDIX F

LIME VERIFICATION TEST DATA

F-1 Stoichiometry and SO_2 Emissions

F-2 pH Data

F-3 Chemical Analyses and Utilization

F-4 Scrubber Operating Data

F-5 SO_2 Concentration Data

TABLE F-1 LIME VERIFICATION TESTS - STOICHIOMETRY AND SO_2 EMISSIONS

TEST NO.	AVERAGE SO_2 ppm		COAL FIRING RATE, lbs/hr	COAL HEATING VALUE, Btu/lb*	AVERAGE LIME SO_2 STOICHIOMETRY	AVERAGE LIME UTILIZATION	AVERAGE SO_2 EMISSIONS lbs/10^6Btu
	INLET	OUTLET					
22	800	309	9916	10,619	0.576	99.4	1.768
23	910	355	7822	11,082	0.572	99.1	2.337
24	720	386	7755	11,082	0.417	98.9	2.620
25	660	265	7658	11,082	0.565	99.0	1.844
26	740	207	9526	11,082	0.710	99.2	1.123
27	735	229	9702	11,082	0.662	99.0	1.260
28	725	271	9225	11,082	0.592	99.2	1.616
29	945	289	12,810	11,139	0.674	97.2	0.880
30	950	265	9694	11,139	0.698	98.1	1.185
31	855	239	9668	11,139	0.710	97.2	1.317
32	550	61	6813	10,707	0.901	97.9	0.498
33	650	21	7492	10,707	0.985	98.0	0.171
34	725	176	7955	10,707	0.746	98.2	1.288
36	700	48	7976	10,707	0.944	98.0	0.362
37	665	48	10,823	10,707	0.938	98.1	0.280

* As Fired

TABLE F-2 AVERAGE pH DATA FOR LIME VERIFICATION TESTS

TEST NO.	DISSOLVER pH	DROP COLLECTOR pH FIRST STAGE	DROP COLLECTOR pH SECOND STAGE	LEVEL TANK pH FIRST STAGE	LEVEL TANK pH SECOND STAGE
22	5.4	4.8	5.4	-	4.6
23	6.2	-	4.6	6.2	6.4
24	5.8	4.9	4.7	5.5	-
25	5.7	5.4	5.4	5.4	5.6
26	6.6	5.4	5.2	6.0	6.4
27	7.1	5.0	4.9	7.1	7.6
28	8.0	5.2	5.1	7.4	8.0
29	7.9	4.9	5.0	7.6	8.4
30	8.3	4.6	4.8	7.7	8.3
31	8.4	5.0	4.7	8.5	8.6
32	8.5	6.0	5.1	9.0	8.8
33	8.6	7.0	5.4	8.6	8.8
34	8.3	5.1	5.3	8.4	8.3
36	8.4	5.9	5.7	8.0	8.4
37	8.6	6.3	5.2	8.6	8.5

TABLE F-3 LIME VERIFICATION TESTS, CHEMICAL ANALYSES (WT.%) AND UTILIZATION

1977 Date	Time	Location*	Test	% Acid Insolubles	%$CaSO_4 \cdot 2H_2O$	%$CaSO_3 \cdot 0.5H_2O$	% $Ca(OH)_2$	% $CaCO_3$	Ignition Loss	% Lime Utilization
3-14	1800	D	22	4.01	42.81	50.76	0	0	3.80	100.00
3-14	1800	S	22	4.83	42.96	49.75	0	0.43	2.61	99.33
3-14	1900	D	22	4.06	40.76	54.05	0	0.55	3.15	99.17
3-14	1900	S	22	3.74	42.91	51.04	0	0.63	2.13	99.03
3-15	0930	D	23	3.41	47.50	48.18	0	0.54	2.86	99.18
3-15	0930	S	23	3.87	47.69	46.60	0	0.64	2.26	99.01
3-15	1030	D	23	3.53	45.44	47.74	0	0.61	2.31	99.05
3-15	1030	S	23	4.39	47.16	45.45	0	0.59	2.26	99.07
3-15	1245	D	24	3.43	46.68	46.74	0	0.68	2.29	98.94
3-15	1245	S	24	3.95	47.64	46.60	0	0.77	2.40	98.81
3-15	1400	D	24	3.25	47.45	45.59	0	0.77	2.06	98.79
3-15	1400	S	24	4.42	48.41	45.45	0	0.55	2.26	99.14
3-15	1445	D	25	4.64	47.74	45.74	0	0.68	2.08	98.94
3-15	1445	S	25	6.59	48.48	45.59	0	0.56	2.13	99.13
3-15	1600	D	25	4.13	49.07	45.59	0	0.56	2.10	99.13
3-15	1600	S	25	4.75	50.08	44.88	0	0.77	2.19	98.81
3-15	1645	D	26	4.29	47.98	46.31	0	0.86	2.15	98.67
3-15	1645	S	26	4.11	49.55	43.87	0	0.52	2.01	99.18
3-15	1800	D	26	4.27	47.74	46.17	0	0.86	2.13	98.67
3-15	1800	S	26	4.73	50.46	44.88	0	0.57	2.13	99.12
3-15	1820	D	27	3.77	49.17	45.74	0	0.77	2.22	98.81
3-15	1820	S	27	3.49	48.98	44.88	0	0.50	2.13	99.22
3-15	1920	D	27	4.30	46.59	47.17	0	0.57	2.17	99.11
3-15	1920	S	27	3.90	50.27	44.88	0	0.68	2.29	98.59
3-15	2000	D	28	6.50	46.59	47.17	0	0.57	2.17	99.11
3-15	2000	S	28	3.37	48.31	45.16	0	0.56	2.19	99.12
3-15	2100	D	28	6.63	46.35	47.75	0	0.45	2.36	99.30
3-15	2100	S	28	3.71	47.83	45.16	0	0.39	2.31	99.38
3-16	1545	D	29	6.15	88.97	3.73	0	1.14	1.70	97.96

* D - Dissolver tank
S - First stage drop collector

TABLE F-4 SCRUBBER OPERATING DATA LIME VERIFICATION TEST

TEST NO.	1977 DATE	SCRUBBER GAS + FLOW (acfmx10^3 @120°F)	SECOND STAGE SLURRY PUMP RATE (gpm)	SLURRY %SOLIDS	AVERAGE PRESSURE DROP (in. H_2O) TOTAL	FIRST STAGE	SECOND STAGE	AVERAGE LIQUID PICKUP (gpm) FIRST STAGE	SECOND STAGE	AVERAGE L/G (gal./10^3 acf) FIRST STAGE	SECOND STAGE
22	3-14	66.4	2400	14.5	19.5	8.5	11.0	990	180	14.9	2.7
23	3-15	62.9	2200	17.7	21.0	10.5	10.5	960	120	15.3	1.9
24	3-15	64.3	2350	16.1	23.5	11.5	12.0	1035	165	16.1	2.6
25	3-15	65.1	2100	18.0	22.3	10.5	11.8	1005	150	15.4	2.3
26	3-15	63.1	2650	19.1	22.4	10.5	11.9	1020	165	16.2	2.6
27	3-15	65.2	2650	20.8	21.4	10.2	11.2	990	150	15.2	2.3
28	3-15	67.2	2250	19.8	22.8	11.0	11.8	1020	180	15.2	2.7
29	3-16	47.9	2600	3.2	19.2	11.8	7.4	1020	150	21.3	3.1
30	3-16	53.2	2550	2.4	17.9	9.0	8.9	1020	225	19.2	4.2
31	3-16	65.4	> 3000	2.4	18.0	8.5	9.5	990	180	15.1	2.8
32	3-17	65.6	2400	9.2	21.0	8.0	13.0	1020	210	15.5	3.2
33	3-17	72.1	2400	10.3	20.7	8.2	12.5	1020	180	14.2	2.5
34	3-17	68.7	2400	10.6	22.5	13.0	9.5	1170	390	17.0	5.7
36	3-17	70.9	2400	11.5	21.5	9.0	12.5	780	600	11.0	8.5
37	3-17	74.4	2500	9.8	19.9	9.2	10.7	1005	225	13.5	3.0

TABLE F-5 LIME VERIFICATION TESTS, SO_2 CONCENTRATION DATA

		SO_2 Concentration (ppm)				% Removal Efficiency*		
Test No.	DuPont/ Wet Test	Inlet	Midpoint	Outlet	Corrected Outlet	First Stage	Second Stage	Overall
22	D	800		340	309			57.20
	W	---		---	---			---
23	D	910	---	390	355	---	---	56.65
	W	---	492	460	---	39.92	---	---
24	D	720		425	386			41.26
	W	---		396	396			39.74
25	D	660	---	292	265	---	---	55.92
	W	---	425	408	---	29.31	---	---
26	D	740	---	228	207	---	---	70.22
	W	---	338	328	---	51.38	---	---
27	D	735		252	229			65.54
	W	---		322	---			---
28	D	725	---	298	271	---	---	58.73
	W	---	350	272	272	46.71	22.29	58.58
29	D	945	---	332	289	---	---	65.48
	W	---	328	242	242	60.82	26.22	71.09
30	D	950	---	305	265	---	---	68.42
	W	---	382	332	---	54.47	---	60.43
31	D	855	---	275	239	---	---	69.03
	W	---	426	379	---	44.79	---	---

TABLE F-5 (CONT.) LIME VERIFICATION TESTS, SO_2 CONCENTRATION DATA

Test No.	DuPont/ Wet Test	SO_2 Concentration (ppm) Inlet	Midpoint	Outlet	Corrected Outlet	% Removal Efficiency * First Stage	Second Stage	Overall
32	D	550	---	64	61	---	---	88.17
	W	---	304	---	---	41.05	---	---
33	D	650	---	22	21	---	---	96.56
	W	---	308	---	---	49.56	---	---
34	D	725	---	185	176	---	---	73.25
	W	---	261	242	---	60.33	---	---
36	D	700	---	50	48	---	---	92.48
	W	---	480	---	---	24.81	---	---
37	D	665	---	55	48	---	---	92.09
	W	---	378	---	---	37.72	---	---

APPENDIX G

LIMESTONE TEST DATA

G-1 Stoichiometry and SO2 Emissions
G-2 pH Data
G-3 Chemical Analyses and Utilization
G-4 Scrubber Operating Data
G-5 SO_2 Concentration Data
G-6 Regression Analysis Results

TABLE G-1 LIMESTONE STATISTICAL TESTS - STOICHIOMETRY AND SO_2 EMISSIONS

TEST NO.	AVERAGE SO_2 ppm INLET	OUTLET	AVERAGE COAL FIRING RATE lbs/hr	AVERAGE COAL HEATING VALUE, Btu/lb	AVERAGE LIME/SO_2 *STOICHIOMETRY	AVERAGE LIMESTONE UTILIZATION	AVERAGE SO_2 EMISSIONS lbs/10^6Btu
38	438	109	4312	10,992	0.800	91.8	1.018
39	425	30	4928	11,003	1.532	60.3	0.181
40	350	33	4531	11,168	1,547	58.2	0.253
41	290	31	3955	10,751	1.424	62.3	0.345
42	300	92	3338	11,003	1.085	62.4	1.232
43	360	23	4158	10,646	1.408	66.2	0.186
44	410	57	4992	10,646	1.187	71.8	0.437
45	320	35	5252	10,646	1.298	68.1	0.342
46	295	70	3984	10,646	1.136	66.1	0.958
47	390	90	5006	10,992	0.859	87.9	0.760
48	410	71	3949	10,992	0.943	86.6	0.674
49	375	90	4765	11,894	1.186	63.4	0.781
50	254	125	3958	10,469	0.625	77.4	1.484
51	483	102	3960	11,481	0.958	80.8	0.753
52	425	194	3631	11,481	0.717	71.9	1.828
53	350	71	5408	11,107	1.193	66.0	0.617
54	375	131	4165	11,107	0.944	67.2	1.513
55	600	107	4158	11,107	1.385	58.4	0.685
56	525	284	4092	11,107	0.593	66.4	2.228
57	375	69	3393	10,992	0.943	85.1	0.781
58	335	55	3966	10,992	1.014	81.4	0.525

*As Fired

TABLE G-2 AVERAGE pH DATA FOR LIMESTONE STATISTICAL TESTS

TEST NO.	DISSOLVER pH	DROP COLLECTOR pH		LEVEL TANK pH	
		FIRST STAGE	SECOND STAGE	FIRST STAGE	SECOND STAGE
38	5.8	5.2	5.3	5.7	5.7
39	5.3	5.2	5.4	5.9	5.8
40	5.6	5.2	5.5	6.1	6.0
41	5.8	5.6	5.9	6.4	5.9
42	5.5	5.4	5.4	6.9	6.3
43	5.5	5.5	5.7	6.2	5.6
44	5.1	4.9	5.1	5.6	5.2
45	5.1	5.0	5.5	5.6	5.8
46	5.7	5.3	5.2	6.4	6.0
47	6.2	5.8	5.6	6.0	6.1
48	5.6	5.5	5.4	6.0	6.0
49	7.7	6.3	6.3	6.6	9.1
50	5.9	5.3	5.2	5.4	6.1
51	5.5	5.4	3.8	4.4	6.2
52	6.1	5.5	5.7	6.0	6.2
53	6.2	5.8	5.7	6.0	6.5
54	6.3	6.0	5.8	6.6	6.1
55	6.7	6.2	6.3	6.1	6.7
56	6.2	5.8	5.7	6.1	6.6
57	5.6	5.5	5.6	6.2	5.7
58	5.6	5.5	5.6	6.2	5.9

TABLE G-3 LIMESTONE TESTS CHEMICAL ANALYSES (WT.%) AND UTILIZATION

1977 Date	Time	Location*	Test	% Acid Insolubles	%$CaSO_4 \cdot 2H_2O$	%$CaSO_3 \cdot 0.5H_2O$	%$MgCO_3$	%$CaCO_3$	% Limestone Utilization
5-11	1720	D	50	3.21	76.93	2.87	1.25	16.40	72.41
5-11	1720	S	50	6.94	74.16	1.43	0.92	18.76	69.01
5-11	1815	D	50	5.39	83.53	1.43	0.77	8.62	83.89
5-11	1815	S	50	6.26	83.00	1.43	0.77	8.35	84.19
5-12	1130	D	51	4.86	85.34	1.72	0.59	9.92	82.75
5-12	1130	S	51	7.04	78.89	3.58	2.39	8.80	80.68
5-12	1230	D	51	3.36	82.67	2.44	2.53	10.87	78.25
5-12	1230	S	51	5.37	84.20	2.58	0.67	10.87	81.37
5-12	1630	D	52	2.78	78.60	1.86	1.15	16.49	72.52
5-12	1630	S	52	6.27	80.99	3.30	0.57	10.50	81.62
5-12	1730	D	52	2.60	70.00	1.72	0.73	21.88	64.88
5-12	1730	S	52	5.40	74.30	2.29	0.69	19.67	68.70
5-16	1600	D	49	2.63	51.61	1.43	0.24	28.43	52.00
5-16	1600	S	49	4.63	74.64	0.72	0.61	19.33	68.67
5-16	1700	D	49	3.49	69.29	1.43	0.90	22.40	63.81
5-16	1700	S	49	4.19	74.11	1.43	0.80	19.90	67.94
5-17	1030	D	54	5.47	72.82	0.00	0.48	21.04	66.21
5-17	1030	S	54	2.58	75.36	0.00	0.77	19.60	68.11
5-17	1410	D	55	1.37	62.45	0.00	1.25	25.24	57.60
5-17	1410	S	55	2.67	63.31	1.43	1.34	24.45	59.28
5-17	1700	D	56	3.01	76.45	0.72	0.79	18.88	69.43
5-17	1700	S	56	2.77	61.40	0.00	1.49	25.31	56.86
5-17	1800	S	56	--	79.08	0.00	2.13	14.49	72.98
5-17	1900	D	53	2.06	69.00	2.87	0.67	22.63	64.38
5-17	1900	S	53	2.46	74.07	0.75	0.71	20.17	67.66
5-19	1015	D	38	3.30	93.75	0.00	0.36	4.09	92.34
5-19	1015	S	38	2.14	92.03	0.00	0.36	4.71	91.24

* D - Dissolver tank
S - First stage drop collector

TABLE G-3 LIMESTONE TESTS CHEMICAL ANALYSES (WT.%) AND UTILIZATION (CONT.)

1977 Date	Time	Location*	Test	% Acid Insolubles	%$CaSO_4 \cdot 2H_2O$	%$CaSO_3 \cdot 0.5H_2O$	%$MgCO_3$	%$CaCO_3$	% Limestone Utilization
5-19	1230	D	47	2.52	89.60	0.57	0.44	7.12	87.30
5-19	1230	S	47	1.83	91.08	0.00	0.56	6.18	88.55
5-19	1515	D	48	3.79	88.54	0.00	0.44	7.62	86.34
5-19	1515	S	48	2.77	72.87	0.00	0.31	6.07	86.81
5-19	1615	S	48	3.62	89.60	0.43	0.29	7.89	86.42
5-19	1700	D	57	4.18	85.53	0.00	0.46	8.12	85.16
5-19	1700	S	57	3.70	89.11	0.00	0.42	8.55	85.13
5-19	1900	D	58	3.15	84.43	0.00	0.47	11.83	79.85
5-19	1900	S	58	3.40	87.49	0.00	0.42	9.92	83.00
5-20	1045	D	41	4.89	68.43	2.29	0.65	22.70	63.91
5-20	1045	S	41	3.65	65.85	0.43	1.13	23.63	60.73
5-23	1500	D	42	4.02	68.09	0.00	0.94	22.72	62.41
5-23	1500	S	42	4.16	68.14	0.00	1.03	22.63	62.41
5-23	1715	D	39	3.06	67.85	0.43	1.32	22.70	62.11
5-23	1715	S	39	3.67	63.03	0.72	2.78	23.02	58.56
5-24	1600	D	40	2.94	63.07	0.00	1.44	24.45	58.36
5-24	1600	S	40	2.41	56.15	0.43	1.88	27.25	52.79
5-24	1700	S	40	6.54	69.29	0.00	0.42	22.77	63.39
5-25	0930	D	45	4.88	74.64	0.43	1.21	19.33	67.80
5-25	0930	S	45	6.37	75.83	0.00	0.96	19.22	68.41
5-25	1150	D	44	3.95	79.18	0.00	0.67	17.76	71.27
5-25	1150	S	44	3.29	79.32	2.15	0.73	17.51	72.22
5-25	1705	D	46	3.57	72.58	0.00	0.52	21.04	66.08
5-25	1705	S	46	5.16	72.63	0.00	0.67	20.92	66.04
5-25	1915	D	43	5.24	71.77	1.43	0.75	21.06	66.12
5-25	1915	S	43	4.72	73.01	0.00	0.84	20.58	66.30

TABLE G-4 SCRUBBER OPERATING DATA LIMESTONE TEST

TEST NO.	1977 DATE	SCRUBBER GAS FLOW (acfmx10^3 120°F)	SECOND STAGE SLURRY PUMP RATE (gpm)	SLURRY %SOLIDS	AVERAGE PRESSURE DROP (in.H_2O) TOTAL	FIRST STAGE	SECOND STAGE	AVERAGE LIQUID PICKUP (gpm) FIRST STAGE	SECOND STAGE	AVERAGE L/G (gal./10^{3}acf) FIRST STAGE	SECOND STAGE
38	5-19	48.8	2280	6.5	17.0	7.5	9.5	1080	690	22.2	14.2
39	5-23	36.0	2550	13.1	16.3	8.8	7.5	1050	435	29.2	12.1
40	5-24	42.8	1910	15.7	15.2	5.2	10.0	435	750	10.2	17.5
41	5-20	52.2	2660	9.0	24.7	12.0	12.7	1755	915	33.6	17.5
42	5-23	54.2	1890	12.9	15.5	9.5	6.0	1320	120	24.4	2.2
43	5-25	39.5	2780	8.1	20.0	12.0	8.0	1515	540	38.3	13.7
44	5-25	44.9	1960	7.8	16.8	7.8	9.0	1020	510	22.7	11.4
45	5-25	60.2	2780	8.8	22.2	7.2	15.0	1050	1260	17.4	20.9
46	5-25	64.0	2050	9.2	11.2	6.0	5.2	630	120	9.8	1.9
47	5-19	51.2	2400	4.4	18.3	8.8	9.5	1440	615	28.1	12.0
48	5-1	45.4	2280	5.0	17.9	9.0	8.9	1440	585	31.7	12.9
49	5-1	54.2	2470	3.6	19.8	9.0	10.8	1500	600	27.7	11.1
50	5-1	54.2	1875	4.7	18.8	6.0	12.8	585	750	10.8	13.8
51	5-1	37.0	2680	2.5	24.8	12.0	12.8	1560	1065	42.1	28.7
52	5-1	43.3	2000	2.8	13.3	7.5	5.8	1050	150	24.2	3.5
53	5-17	57.5	2720	2.0	25.3	15.3	10.0	1710	525	29.7	9.1
54	5-17	58.9	1750	1.3	16.3	7.5	8.8	945	240	16.1	4.1
55	5-1	32.6	2660	2.9	18.4	7.0	11.4	945	780	29.0	24.0
56	5-1	39.3	1930	1.5	10.0	5.0	5.0	495	90	12.6	2.3
57	5-19	46.5	2250	7.2	18.0	9.0	9.0	1380	525	29.7	11.3
58	5-19	45.9	2280	4.6	18.0	9.0	9.0	1395	480	30.4	10.5

+ Saturated gas flow inside scrubber =

$$\text{(Inlet scfm)} \times \left[1 + \frac{(T\ \text{inlet} - 120^{\circ}F)\ CP_g}{H1 \times MW_L}\right] \times \frac{580^{\circ}R}{492^{\circ}R}$$

H1=970 Btu/lb water
MW_L = 18lb/lb mole
CP_g= 7.26 Btu/lb mole-°F

TABLE G-5 LIMESTONE TESTS, AVERAGE SO_2 CONCENTRATION DATA

		SO_2 Concentration (ppm)				% Removal Efficiency *		
Test No.	DuPont/ Wet Test	Inlet	Midpoint	Outlet	Corrected Outlet	First Stage	Second Stage	Overall
38	D	438	---	122	109	---	---	73.46
	W	354	169	81	81	49.28	52.07	75.69
39	D	425	---	34	30	---	---	92.46
	W	411	76	43	43	80.24	43.42	88.82
40	D	350	---	38	33	---	---	90.02
	W	332	158	57	57	49.64	63.92	81.83
41	D	290		35	31			88.73
	W	270		20	20			92.20
42	D	300		105	92			67.74
	W	233		60	60			72.91
43	D	360		26	23			93.22
	W	294		15	15			94,58
44	D	410	---	65	57	---	---	85.18
	W	358	119	64	64	64.58	46.22	80.95
45	D	320	---	40	35	---	---	88.43
	W	298	114	31	31	59.55	72.81	89.00
46	D	295	---	80	70	---	---	75.07
	W	208	105	60	60	46.96	42.86	69.69
47	D	390	---	101	90	---	---	75.49
	W	330	120	42	42	61.37	65.00	86.48

TABLE G-5 (CONT.) LIMESTONE TESTS, AVERAGE SO_2 CONCENTRATION DATA

		SO_2 Concentration (ppm)				% Removal Efficiency *		
Test No.	DuPont/ Wet Test	Inlet	Midpoint	Outlet	Corrected Outlet	First Stage	Second Stage	Overall
48	D	410	---	80	71	---	---	81.55
	W	320	139	70	70	53.71	49.64	76.69
49	D	375	---	100	90	---	---	74.82
	W	330	140	48	48	55.49	65.71	84.74
50	D	254	---	120	125	---	---	48.38
	W	270	166	53	53	35.50	68.07	79.41
51	D	483	---	112	102	---	---	77.39
	W	449	163	41	41	61.13	74.85	90.22
52	D	425	---	212	194	---	---	51.55
	W	395	190	129	129	48.94	32.11	65.33
53	D	350		80	71			78.74
	W	309		46	46			84.40
54	D	375	---	147	131	---	---	63.41
	W	312	166	106	106	44.27	36.14	64.42
55	D	600	---	120	107	---	---	80.96
	W	563	202	80	80	61.70	60.40	84.83
56	D	525	---	318	284	---	---	42.26
	W	438	249	204	204	39.32	18.07	50.29
57	D	375	---	78	69	---	---	80.33
	W	278	112	48	48	57.20	57.14	81.66
58	D	335	---	62	55	---	---	82.60
	W	258	84	46	46	65.48	45.24	81.10

* DuPont SO_2 Removal based on corrected outlet value

APPENDIX G-6

Regression Analysis of the Limestone Test Data

Equation (5.1) represents the best two-coefficient model obtained from the analysis of the lime test data. The choice of limestone/SO_2 stoichiometry and slurry circulation rate for the regression analysis was based on the results of the statistical screening tests described in Section 5.

A General Electric regression analysis program was used to obtain the exponents in equation (5.1). A copy of the computer printout indicating the coefficients, correlations and observed and predicted values of the natural logs of the removal efficiency is attached.

The analysis was run on a model in the following form:

ln (SO_2 removal efficiency %) = Z1 X ln (slurry circulating rate, gpm) + Z2 X ln (limestone/SO_2 stoichiometry).

```
INDEPENDENT      REGRESSION       CHECK          STANDARD        T          SIG
 VARIABLE        COEFFICIENT      NUMBER            ERROR      VALUE       LEVEL
 Z1                0.554521     -1.08E-16   0.295509E-02  187.650    100.00%
 Z2                0.523089     -6.36E-19   0.823090E-01    6.355    100.00%

CODE --?2



            ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL-

   SOURCE          DF                    SS                  MS-

 REGRESSION         2                  390.50              195.25
      ERROR        19                 0.20222          0.10643E-01-
      TOTAL        21                  390.71

          18344.943  =  F-RATIO, A 100.00% VALUE.

             0.9997  =  MULTIPLE CORRELATION COEFFICIENT.
             0.9995  =  INDEX OF DETERMINATION.
             0.9994  =  "ADJUSTED" INDEX OF DETERMINATION.
                         [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

            0.10317  =  STANDARD ERROR OF ESTIMATE
                         2.395% OF MEAN OF Y3        -


CODE --?1



    CASE          OBSERVED         PREDICTED-
    NO.            VALUE            VALUE          RESIDUAL        % DEVIATION

      1           4.4856           4.5564       -0.70828E-01          -1.55
      2           4.1496           4.1085        0.41171E-01           1.00
      3           4.3662           4.4764         -0.11021            -2.46
      4           4.2157           4.2238       -0.80745E-02          -0.19
      5           4.4856           4.5347       -0.49111E-01          -1.08

      6           3.8791           3.9290       -0.49933E-01          -1.27
      7           4.3151           4.3912       -0.76102E-01          -1.73
      8           4.3184           4.2925        0.25934E-01           0.60
      9           4.3489           4.3558       -0.69438E-02          -0.16
     10           4.4448           4.2947          0.15011             3.50

     11           4.5350           4.5772       -0.42235E-01          -0.92
     12           3.9426           4.0430         -0.10047            -2.49
     13           4.3940           4.5415         -0.14752            -3.25
     14           4.5000           4.4417        0.58349E-01           1.31
     15           4.5268           4.5720       -0.45259E-01          -0.99

     16           3.7438           3.9218         -0.17792            -4.54
     17           4.2967           4.1708          0.12594             3.02
     18           4.3240           4.2371        0.86930E-01           2.05
     19           4.4012           4.2552          0.14606             3.43
     20           4.3861           4.2478          0.13833             3.26

     21           4.4140           4.2927          0.12128             2.83-

         STANDARD ERROR OF THE ESTIMATE =         0.10317
```

APPENDIX H

PARTICULATE TEST DATA SUMMARY

H-1 Particulate Collection Efficiency and Particulate Emission Rate Data

H-2 Mechanical Collector Efficiency Calculations

H-3 Scrubber Inlet Particle Size Distribution

H-4 Particulate Penetration Model Regression Analyses

H-5 Fractional Collection Efficiencies

TABLE H-1: PARTICULATE COLLECTION EFFICIENCY AND PARTICULATE EMISSION RATE

Test No.	Date	Particulate Wt. Collected (gms) Inlet	Particulate Wt. Collected (gms) Outlet	Concentration (Grains/SCF Dry) Inlet	Concentration (Grains/SCF Dry) Outlet	Collection Efficiency, %	Total Pressure Drop (in. H_2O)	Boiler Firing Rate MM Btu/hr	Particulate Emissions (lbs/10^6 Btu)	Orsat Analyses Inlet % CO_2	Orsat Analyses Inlet % O_2	Orsat Analyses Outlet % CO_2	Orsat Analyses Outlet % O_2	Inlet % Excess Air
1	12-16-76	0.7024	0.0894	0.2403	0.0570	76.27	16.0	155.2	0.171	8.2	11.0	7.4	12.2	106
2R	4-5-77	0.5717	0.1682	0.2736	0.1169	57.29	20.5	133.1	0.292	-	-	-	-	-
4	12-15-76	0.9050	0.1509	0.2738	0.0539	80.30	24.0	165.9	0.177	7.1	12.3	7.0	12.4	137
10	12-18-76	0.7563	0.2996	0.2624	0.1035	60.55	17.5	153.3	0.314	8.6	11.0	8.2	12.0	107
11	12-18-76	0.5239	0.2755	0.1700	0.0854	49.76	18.0	169.5	0.244	7.8	11.8	7.2	12.2	125
12R	4-7-77	0.2236	0.0847	0.1139	0.0539	52.68	10.6	-	0.210	-	-	-	-	-
15	12-13-76	0.4742	0.2845	0.1828	0.1024	43.99	19.3	193.9	0.219	9.0	10.6	8.6	10.8	100
18R	4-6-77	0.6003	0.1832	0.2463	0.1139	53.74	17.5	114.6	0.311	-	-	-	-	-
2	12-17-76	0.3930	0.2111	0.1654	0.1073	35.16	21.5	-	-	7.6	12.0	8.8	12.1	-
7	4-12-77	0.1678	0.0423	0.0785	0.0334	57.53	21.8	77.7	0.189	-	-	-	-	-
12	12-19-76	0.9368	0.1504	0.2543	0.0439	82.73	18.0	-	-	6.2	13.0	6.2	13.2	-
18	12-20-76	0.4003	0.1312	0.1509	0.0573	62.05	25.0	-	-	8.8	9.8	8.8	10.4	-
5-11-77*		-	-	-	0.0144	-	19.0	-	0.146	-	-	-	-	-
5-11-77*		-	-	-	0.0188	-	19.0	-	0.188	-	-	-	-	-
5-11-77*		-	-	-	0.0211	-	19.0	-	0.219	-	-	-	-	-

*These tests were not part of the fractional efficiency test program. EPA method 5 was used for these tests.

APPENDIX H-2

MECHANICAL COLLECTOR EFFICIENCY CALCULATIONS FOR EACH MECHANICAL COLLECTOR
ΔP = 2.0 in. W.C. FLY ASH S.G. = 2.0 gm/cm^3

First Mechanical Collector Dp, Microns	Collector Efficiency	Wt. of Particulates	Wt. Collected	Wt. Uncollected	Cumulative Wt.% of Uncollected Particulates
1	4	0.5	-0-	0.50	3.74
1-3	10	4.0	0.40	3.60	30.67
3-5	44	5.5	2.42	3.08	53.71
5-7	63	6.0	4.08	1.92	68.07
7-9	83	6.0	4.98	2.02	83.18
9-11	95	5.0	4.75	0.25	85.05
11-19	96	17.0	16.32	0.68	90.14
20+	98	66.0	64.68	1.32	100.00
		100.0#	86.63#	13.37#	

Second Mechanical Collector Dp, Microns	Collector Efficiency	Wt. of Particulates	Wt. Collected	Wt. Uncollected	Cumulative Wt.% of Uncollected Particulates
1	4	0.5	-0-	0.50	7.72
1-3	10	3.6	0.36	3.24	57.72
3-5	44	3.08	1.36	1.72	84.27
5-7	68	1.92	1.31	0.61	93.68
7-9	83	2.02	1.68	0.34	98.93
9-11	95	0.25	0.24	0.01	99.08
11-19	96	0.68	0.65	0.03	99.54
20+	98	1.32	1.29	0.03	100.00
		13.37#	6.89#	6.48#	

Total Collected - 93.52# for 93.52% Removal Efficiency

TABLE H-3

SCRUBBER INLET PARTICLE SIZE DISTRIBUTION

Date	Start	S.G.	Temp.	Dia., μ	Cum. Wt.%
5/25/76	1335 hrs.	1.3	220°F	10.0	99.99
				6.3	99.12
				4.2	96.12
				2.9	88.66
				1.8	77.06
				0.94	65.60
				0.53	56.07
				0.38	47.51
				<0.38	39.50
5/24/76	1400 hrs.	1.3	232°F	15.6	99.99
				9.66	99.62
				6.44	97.75
				4.48	95.13
				2.82	90.64
				1.45	81.65
				0.90	66.67
				0.61	49.44
				<0.61	44.57
5/19/76	1400 hrs.	1.3	222°F	11.49	--
				7.09	--
				4.80	99.98
				3.35	98.70
				2.10	95.63
				1.08	87.17
				0.65	75.89
				0.44	62.56
				<0.44	48.20
5/19/76	1645 hrs.	1.3	222°F	11.49	100.00
				7.09	99.53
				4.80	96.73
				3.35	92.28
				2.10	88.19
				1.08	81.29
				0.65	72.51
				0.44	59.30
				<0.44	45.96

APPENDIX H-4

This section of Appendix H contains the results of a series of regression analyses which were performed to determine the coefficients in the one and two stage particulate penetration models. As stated in Section 6, a model based on inertial impaction was selected. Coefficients for both models for particles in the following size ranges were developed:

0.3 to 0.5 micron, 0.5 to 1.0 micron,
1.0 to 2.0 microns and 2.0 to 5.0 microns.

The following diameters were used to represent an average particle in each range:

0.4 micron, 0.7 micron, 1.4 microns and 3.2 microns.

Input data for these regression analyses included liquid pickup and flue gas temperature data collected during the particulate tests and the fractional particulate collection efficiency data selected from the results of the Andersen Impactor tests run for this part of the program.

A total of eight regression analyses were performed. They are presented in the following order.

Particle Size Range Micron	No. of Stages	Data File Name
0.3-0.5	2	Final 1A
0.3-0.5	1	Final 1A
0.5-1.0	2	Final 2A
0.5-1.0	1	Final 2A
1.0-2.0	2	Final 3A
1.0-2.0	1	Final 3A
2.0-5.0	2	Final 4
2.0-5.0	1	Final 4

The data files listed above are presented first. Each line in

Final 4

99.99	1200	600	900
98.78	1400	840	940
95.04	1050	540	933
98.28	1100	600	938
97.66	780	450	952
99.99	1350	810	938
95.70	1050	1140	908

```
REGRESSION ANALYSIS FOR 0.3 td 0.5 microns Particles

TWO STAGE MODEL                    DATA FILE:  FINAL 1A



INDEPENDENT     REGRESSION      CHECK           STANDARD       T        SIG
 VARIABLE       COEFFICIENT     NUMBER            ERROR      VALUE     LEVEL
  Z1           0.375848E-06   -2.04E-13     0.206379E-05     0.182     13.57%
  Z2          -0.268697E-02   -1.30E-16     0.264399E-02    -1.016     63.30%

CODE --?12


        ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL-

   SOURCE        DF                 SS              MS

REGRESSION        2              1.6887          0.84434
     ERROR        4              0.32938       0.82346E-01-
     TOTAL        6              2.0181-

           10.254   =  F-RATIO, A  97.34% VALUE.

           0.9148   =  MULTIPLE CORRELATION COEFFICIENT.
           0.8368   =  INDEX OF DETERMINATION.
           0.7552   =  "ADJUSTED" INDEX OF DETERMINATION.
                       [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

          0.28696   =  STANDARD ERROR OF ESTIMATE
                     -58.883% OF MEAN OF Y2         -

CODE --?1


    CASE          OBSERVED         PREDICTED
    NO.            VALUE             VALUE            RESIDUAL     % DEVIATION

     1           -0.65843          -0.51397          -0.14446         28.11-
     2            -1.0985          -0.74674          -0.35173         47.11
     3           -0.16536          -0.46376           0.29840        -64.34
     4           -0.23587          -0.52237           0.28650        -54.85
     5           -0.41057          -0.32614       -0.14428E-01         3.64

     6           -0.35528          -0.47119           0.11590        -24.60

      STANDARD ERROR OF THE ESTIMATE =                0.28696
      REGRESSION ANALYSIS FOR 0.5 TO 1.0 MICRON PARTICLES

      TWO STAGE MODEL                        DATA FILE:  FINAL 2A

INDEPENDENT     REGRESSION      CHECK          STANDARD       T        SIG
 VARIABLE       COEFFICIENT     NUMBER            ERROR     VALUE     LEVEL
 Z1            0.518732E-06   -1.08E-12   0.978248E-06     0.530    38.97%
 Z2           -0.229168E-02   -1.19E-15   0.941933E-03    -2.433    95.90%

CODE --?2


          ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL-

   SOURCE         DF                  SS                  MS

 REGRESSION        2                8.7278              4.3639-
      ERROR        8                3.8934             0.48667
      TOTAL       10                12.621-

            8.967  =  F-RATIO, A  99.09% VALUE.

           0.8316  =  MULTIPLE CORRELATION COEFFICIENT.
           0.6915  =  INDEX OF DETERMINATION.
           0.6144  =  "ADJUSTED" INDEX OF DETERMINATION.-
                       [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

          0.69762  =  STANDARD ERROR OF ESTIMATE
                     -74.903% OF MEAN OF Y2

CODE --?1


   CASE         OBSERVED         PREDICTED
   NO.           VALUE             VALUE            RESIDUAL       % DEVIATION

    1           -1.3039          -0.64634          -0.65759          101.74
    2           -2.0161           -1.2398          -0.77631           62.62
    3          -0.52481          -0.58458       0.59771E-01          -10.22
    4          -0.31119          -0.66663           0.35544          -53.32
    5          -0.24913          -0.51052           0.26139          -51.20

    6           -1.2061           -1.2416       0.35482E-01           -2.86
    7          -0.21818          -0.93626           0.71808          -76.70-
    8          -0.77444          -0.66201          -0.11242           16.98
    9           -1.9243          -0.68159           -1.2428          182.33
   10          -0.73534           -1.5509           0.76554          -49.36

       STANDARD ERROR OF THE ESTIMATE =             0.69762
```

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```
             REGRESSION ANALYSIS FOR 1.0 TO 2.0 MICRON PARTICLES

             TWO STAGE MODEL                    DATA FILE:  FINAL 3A


INDEPENDENT       REGRESSION       CHECK            STANDARD        T          SIG
 VARIABLE         COEFFICIENT      NUMBER              ERROR      VALUE       LEVEL
  Z1            -0.210480E-05    -5.24E-13     0.895516E-06    -2.350      94.89%
  Z2            -0.477507E-03    -2.98E-15     0.962452E-03    -0.496      36.50%

CODE --72



              ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL

   SOURCE          DF                       SS                 MS

 REGRESSION         2                    70.314             35.157
      ERROR         7                    9.4782             1.3540
      TOTAL         9                    79.792

              25.965  =  F-RATIO, A  99.94% VALUE.

              0.9387  =  MULTIPLE CORRELATION COEFFICIENT.
              0.8812  =  INDEX OF DETERMINATION.
              0.8473  =  "ADJUSTED" INDEX OF DETERMINATION.
                          [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

              1.1636  =  STANDARD ERROR OF ESTIMATE
                        -41.797% OF MEAN OF Y2


CODE --71


    CASE          OBSERVED           PREDICTED
    NO.            VALUE              VALUE              RESIDUAL        % DEVIATION

     1            -4.5013            -2.9669            -1.5344            51.72
     2            -3.7136            -3.6208       -0.92804E-01             2.56
     3            -2.6783            -2.6469       -0.31444E-01             1.19
     4            -1.2463            -2.8022             1.5559           -55.52
     5            -1.9706            -2.0161        0.45476E-01            -2.26

     6            -2.0101            -1.0106           -0.99955            98.91
     7            -2.8827            -3.4883            0.60560           -17.36
     8            -4.1356            -2.6808            -1.4548            54.27
     9            -1.9175            -3.0171             1.0996           -36.45

         STANDARD ERROR OF THE ESTIMATE =                 1.1636
```

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```
       REGRESSION ANALYSIS FOR 2.0 TO 5.0 MICRON PARTICLES

       TWO STAGE MODEL                      DATA FILE:  FINAL 4

INDEPENDENT    REGRESSION      CHECK_          STANDARD      T        SIG
VARIABLE       COEFFICIENT     NUMBER_            ERROR     VALUE     LEVEL
Z1           -0.232419E-05    -2.13E-11    _0.720005E-06   -3.228    97.67%
Z2            0.709920E-03    -1.98E-14    _0.819968E-03    0.866    57.33%

.JDE --?2



        ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL-

   SOURCE           DF        _          SS               MS

REGRESSION           2        _        154.52            77.261
      ERROR          5        _        9.3926            1.9785
      TOTAL      _   7                 164.41-

       39.050  _=  F-RATIO, A  99.91% VALUE.

       0.9694   =  MULTIPLE CORRELATION COEFFICIENT.-
       0.9398   =  INDEX OF DETERMINATION.
       0.9158   =  "ADJUSTED" INDEX OF DETERMINATION.
                    [COMPUTED_FROM MOMENTS ABOUT THE ORIGIN]

       1.4066   = _STANDARD ERROR OF ESTIMATE
                  _-30.585% OF MEAN OF Y2

CODE --?1


  CASE        OBSERVED        PREDICTED-
  NO.          VALUE            VALUE_          RESIDUAL      % DEVIATION

   1         -6.9085          -5.1129          -1.7956          35.12
   2         -4.4068          -5.8130           1.4063         -24.19
   3         -3.0041          -4.5426           1.5386         -33.37
   4         -4.0633          -4.6972          0.63397         -13.50
   5         -3.7554          -3.3070         -0.44845          13.56

   6         -6.9085          -5.5975          -1.3110          23.42
   7         -3.1469          -3.1018     -0.45113E-01           1.45
      STANDARD ERROR OF THE ESTIMATE =          1.4066-
```

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REGRESSION ANALYSIS FOR 0.3 TO 0.5 MICRON PARTICLES

SINGLE STAGE MODEL   DATA FILE: FINAL 1A

```
INDEPENDENT      REGRESSION      CHECK         STANDARD      T         SIG
 VARIABLE        COEFFICIENT     NUMBER           ERROR     VALUE      LEVEL
 Z2           -0.221377E-02    -4.51E-17   0.439410E-03   -5.038     99.60%

CODE --?2


         ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL

   SOURCE          DF                SS                MS

 REGRESSION        1               1.6859          1.6859-
      ERROR        5               0.33211      0.66423E-01
      TOTAL        6                2.0131-

         25.382  =  F-RATIO, A  99.60% VALUE.

         0.9140  =  MULTIPLE CORRELATION COEFFICIENT.-
         0.8354  =  INDEX OF DETERMINATION.
         0.8025  =  "ADJUSTED" INDEX OF DETERMINATION.
                     [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

        0.25773  =  STANDARD ERROR OF ESTIMATE
                   -52.884% OF MEAN OF Y2

CODE --?1


   CASE          OBSERVED         PREDICTED
   NO.             VALUE            VALUE            RESIDUAL       % DEVIATION

    1           -0.65843         -0.53131          -0.12712           23.93
    2            -1.0985         -0.74383          -0.35470           47.69
    3           -0.16536         -0.47817           0.31281          -65.42-
    4           -0.23587         -0.53131           0.29543          -55.60
    5           -0.41057         -0.39848       -0.12092E-01           3.03

    6           -0.35528         -0.42504        0.69760E-01          -16.41

       STANDARD ERROR OF THE ESTIMATE =            0.25773-
```

```
          REGRESSION ANALYSIS FOR 0.5 TO 1.0 MICRON PARTICLES

          SINGLE STAGE MODEL                    DATA FILE:  FINAL 2A

INDEPENDENT     REGRESSION      CHECK_          STANDARD      T         SIG
VARIABLE        COEFFICIENT     NUMBER_           ERROR      VALUE     LEVEL
Z2            -0.185015E-02   -2.95E-17   _0.422405E-03     -4.380    99.82%

CODE --?2



           ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL
   SOURCE           DF         _          SS                 MS

 REGRESSION          1        _        8.5910             8.5910
      ERROR          9         _       4.0302             0.44780
      TOTAL         10                 12.621-

           19.185   =  F-RATIO, A  99.82% VALUE.

           0.8250   =  MULTIPLE CORRELATION COEFFICIENT.-
           0.6807 _ =  INDEX OF DETERMINATION.
           0.6452   =  "ADJUSTED" INDEX OF DETERMINATION.
                         [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

          0.66918   =  STANDARD ERROR OF ESTIMATE-
                     -71.850% OF MEAN OF Y2         -

CODE --?1


  CASE          OBSERVED         PREDICTED-
  NO.            VALUE             VALUE_          RESIDUAL       % DEVIATION

   1            -1.3039          -0.77706         -0.52686          67.80
   2            -2.0161           -1.0879         -0.92822          85.32
   3           -0.52481          -0.69936          0.17455         -24.96
   4           -0.31119          -0.77706          0.46588         -59.95
   5           -0.24913          -0.58280          0.33367         -57.25

   6            -1.2061           -1.0490         -0.15706          14.97
   7           -0.21818           -1.0490          0.83086         -79.20-
   8           -0.77444          -0.62165         -0.15279          24.58
   9            -1.9243          -0.77706          -1.1473         147.64
  10           -0.73534           -1.4764          0.69108         -46.81

       STANDARD ERROR OF THE ESTIMATE =            0.66918-

----    --
```

```
        REGRESSION ANALYSIS FOR 1.0 TO 2.0 MICRON PARTICLES

        SINGLE STAGE MODEL              DATA FILE:  FINAL 3A


INDEPENDENT     REGRESSION      CHECK_          STANDARD       T        SIG
 VARIABLE       COEFFICIENT     NUMBER _           ERROR     VALUE     LEVEL
 Z1           -0.251383E-05    1.26E-12 _ 0.332788E-06     -7.554     99.99%

CODE --?2


          ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL

    SOURCE          DF          _           SS              MS

 REGRESSION          1          _        69.981          69.981
      ERROR          8          _        9.8115          1.2264
      TOTAL          9                   79.792-

            57.061   =_ F-RATIO, A  99.99% VALUE.

            0.9365   =  MULTIPLE CORRELATION COEFFICIENT.
            0.8770   =  INDEX OF DETERMINATION.
            0.8617   =  "ADJUSTED" INDEX OF DETERMINATION.-
                         [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

            1.1074   = _STANDARD ERROR OF ESTIMATE
                       ±39.779% OF MEAN OF Y2       -

CODE --?1


    CASE          _OBSERVED          PREDICTED-
    NO.             VALUE              VALUE            RESIDUAL         % DEVIATION

     1             -4.5013            -3.0644            -1.4369            46.89
     2             -3.7136            -3.6537       -0.59853E-01             1.64
     3             -2.6783            -2.7301        0.51772E-01            -1.90-
     4             -1.2463            -2.8677             1.6214           -56.54
     5             -1.9706            -2.0486        0.77975E-01            -3.81

     6             -2.0101           -0.56024            -1.4499           258.80-
     7             -2.8827            -3.5195            0.63676           -18.09
     8             -4.1356            -2.7227            -1.4129            51.89-
     9             -1.9175            -2.6932            0.77571           -28.80

        STANDARD ERROR OF THE_ESTIMATE =              1.1074
```

```
                REGRESSION ANALYSIS FOR 2.0 TO 5.0 MICRON PARTICLES

                SINGLE STAGE MODEL            DATA FILE:  FINAL 4


INDEPENDENT     REGRESSION     CHECK_        STANDARD      T        SIG
VARIABLE       COEFFICIENT    NUMBER_          ERROR     VALUE     LEVEL
Z1            -0.172437E-05  -2.95E-12  _0.191930E-06   -8.984    99.99%


CODE --?2



            ANALYSIS OF VARIANCE FOR THE NO-INTERCEPT MODEL

   SOURCE        DF         _           SS              MS-

REGRESSION        1         _        153.04          153.04
     ERROR        6         _        11.376          1.8959-
     TOTAL        7                  164.41-

            80.719  =  F-RATIO, A  99.99% VALUE.-

            0.9648  =  MULTIPLE CORRELATION COEFFICIENT.-
            0.9308_ =  INDEX OF DETERMINATION.
            0.9193  =  "ADJUSTED" INDEX OF DETERMINATION.
                        [COMPUTED FROM MOMENTS ABOUT THE ORIGIN]

            1.3769  = _STANDARD ERROR OF ESTIMATE-
                    -29.940% OF MEAN OF Y2        -


CODE --?1


   CASE          _OBSERVED        PREDICTED-
   NO.             VALUE            VALUE_           RESIDUAL      % DEVIATION

    1             -6.9085          -4.8046          -2.1039          43.79
    2             -4.4068          -5.7286           1.3219         -23.07
    3             -3.0041          -4.2804           1.2764         -29.32
    4             -4.0633          -4.4963          0.43301          -9.63
    5             -3.7554          -3.2120         -0.54344          16.92

    6             -6.9085          -5.5182          -1.3903          25.20
    7             -3.1469          -4.2227           1.0758         -25.43-

      STANDARD ERROR OF THE ESTIMATE =          1.3769-
```

TABLE H-5 FRACTIONAL COLLECTION EFFICIENCIES

Particle Size Range, Microns

Test No.	0.3-0.5	0.5-1.0	1.0-2.0	2.0-5.0
1	48.23	72.85	98.89	99.9
2R	25.66	27.08	91.83	______
4	66.66	86.68	97.56	98.78
10	15.24	40.83	93.13	95.04
11	21.01	26.74	71.74	98.28
12R	21.93	59.46	______	______
15	33.67	22.05	86.06	97.66
18R	______	70.06	86.60	______
2	______	19.60	94.40	99.90
7	29.90	53.90	______	______
12	______	85.40	98.40	______
18	______	54.40	88.30	95.70

Note: This data was used to develop particulate performance models

APPENDIX J

R-C/BAHCO SCRUBBER OPERATING LOG

STARTUP MARCH 11, 1976 11:00 p.m.

Date	Duration (of outage, hrs*)	Comments
4/14/76	15	Inspection of scrubber
	252	Second stage slurry pump liner collapsed
5/3/76	57	Modify scrubber spray manifolds
5/5/76	16	Unknown
5/7/76	226	Repair booster fan bearing
6/4/76	7	Low water level in dissolver tank
	1	Unknown
6/7/76	2	Repack 2nd stage slurry pump
6/8/76	16	Replace belt on 2nd stage slurry pump
6/9/76	5	Loss of fan bearing cooling water
	11	Loss of plant air
6/10/76	1	Power outage
	648	Heat plant shutdown, installation of thickener mechanism and resealing wood thickener tank
7/7/76	2	Control panel maintenance
7/13/76	10	Unknown
	1	Fan vibration
7/14/76	3	Loss of fan bearing cooling water
7/16/76	2	Lime feeder not operating
7/15/76	1	Power outage
7/19/76	3	Training of operators
7/20/76	1	Training of operators
7/22/76	16	Replace sludge pump diaphragm
7/26/76	4	Training
7/26/76	41	Replace torque limiter on lime slaker
7/28/76	759	Repair and modification of fan support

*Outages which ocurred in one month and carried over to the next month are underlined.

APPENDIX J (Cont)

Date	Duration (of outage, hrs*)	Comments
8/30/76	19	Replace lime slaker conveyor motor
8/31/76	16	Lime dissolver level controls malfunction, system shutdown overnight
9/1/76	16	See 8/31/76
9/2/76	16	See 8/31/76
9/3/76	1	Clean blockage in mechanical collector hopper
9/7/76	5	Repack 2nd stage slurry pump and clean blockage in mechanical collector hopper
9/24/76	220	Heat plant outage + realign and balance booster fan
10/5/76	0.5	Inadvertent
10/8/76	0.5	Control panel maintenance
10/12/76	21	Loss of fan bearing cooling water
10/13/76	24	Loss of fan bearing cooling water
10/14/76	1	Loss of fan bearing cooling water
10/14/76	18	Remove and clean plugged sludge line to the pond
10/16/76	64	Repair hole in slurry line
10/19/76	1	Loss of power to control panel
10/28/76	6	Control panel maintenance
10/28/76	0.5	Unknown
10/28/76	0.5	Overload fan motor
10/28/76	880	Repair of the fan thrust bearing
12/6/76	1	Power outage
12/10/76	3	Maintenance of 2nd stage slurry pump packing
12/11/76	23	Loss of water in heat plant

APPENDIX J (Cont.)

Date	Duration (of outage, hrs*)	Comments
12/14/76	2	Changed oil in fan bearing
12/21/76	3	Frozen air lines to blowdowns
12/22/76	4	Frozen air lines to blowdowns
12/24/76	1	Overloaded fan motor
12/30/76	2	Frozen air lines to blowdowns
1/4/77	2	Frozen air lines to blowdowns
1/5/77	2	Repack 2nd stage slurry pump
1/20/77	3	Repack 2nd stage slurry pump
1/21/77	3	Frozen air line to by-pass damper
1/25/77	3	Frozen air line to blowdowns
1/26/77	11	Remove accumulated grit from 2nd stage
1/28/77	4	Frozen air line to by-pass damper
2/1/77	7	Replace blowdown valves
2/2/77	55	Replace blowdown valves
2/4/77	1	Unknown
2/6/77	1	Frozen air line to by-pass damper
2/9/77	7	Remove grit accumulation from slurry line
2/10/77	1	Repair frozen valve
2/11/77	1	Maintenance on booster pump controls
2/14/77	1	Clear 1st stage blowdown valve
2/15/77	1	Repair frozen valve
2/17/77	2	Repair frozen valve
2/24/77	3	Repack 2nd stage slurry pump
2/27/77	5	Overloaded fan motor
3/1/77	206	Repair bearings in water booster pump
3/10/77	0.5	Changed oil in fan bearing
3/12/77	39	Modify control panel wiring

APPENDIX J (Cont.)

Date	Duration (of outage, hrs.*)	Comments
3/14/77	0.5	Inadvertent
3/14/77	0.5	Changed oil in fan bearing
3/16/77	2	Preparation for EPA tests
3/18/77	0.5	Inspection of scrubber interior
3/24/77	29	Removal of grit accumulation from scrubber
4/1/77	1	Check low water level shutdown
4/4/77	2	Replace belt on 2nd stage slurry pump
4/6/77	5	Overloaded fan motor
4/8/77	0.5	Control panel maintenance
4/12/77	0.5	Install EPA test equipment
4/13/77	430	Repair and modification of fan
5/9/77	19	Fan bearing resistance temp. detector (RTD) inoperative
5/10/77	10	RTD inoperative
5/11/77	1	Repair RTD
5/12/77	0.5	Control panel maintenance
5/12/77	1	Unknown
5/13/77	71	Replace lime slaker motor
5/16/77	0.5	Inadvertent
5/19/77	0.5	Change oil in fan bearing
5/25/77	2	Repack 1st stage slurry pump
5/27/77	1	Inadvertent

APPENDIX K

SULFUR DIOXIDE PERFORMANCE TEST RESULTS

K-1 SO_2 Performance Test Results

K-2 Gas Flow and Coal Firing Rate Calculations

K-3 SO_2 Emission Rate Calculations

APPENDIX K-1

SO_2 PERFORMANCE TEST RESULTS

On September 12, 1976, Research-Cottrell personnel performed a series of three (3) tests to determine the rate of sulfur dioxide emissions from a Bahco flue gas desulfurization facility at Rickenbacker Air Force Base, Ohio. These tests, conducted according to Method 6 stipulated by the U.S. Environmental Protection Agency, showed the Bahco facility to be operating in compliance with the guarantee stipulated by Research-Cottrell, Inc. to the U.S. Air Force with regard to SO_2 emissions in the stack gases.

The results of these tests are presented in Table J-1. Note that the average SO_2 emission rate obtained for the three tests was 0.8347 lbs. per million Btu, 16% below the maximum acceptable rate of 1.0 lb. per million Btu.

At the time that these tests were performed, the R-C/Bahco scrubbing system was being operated by automatic controls which provide for, among other things, automatic lime feed control. This lime feed control is designed to regulate the lime additions to the system to meet emission requirements and at the same time to minimize lime consumption.

TABLE K-1 SO_2 PERFORMANCE RESULTS

Gas Volume Collected, ft^3	15.8363	15.4750	15.5230
SO_4 = Level, gm/l	0.2027	0.1572	0.1293
SO_2 Emission Rate, lbs/hr	52.35	42.34	34.72
SO_2 Emission Rate, Lbs/million Btu	1.0243	0.8130	0.6667

Average SO_2 Emission Rate = 0.8347 lb/million Btu

TABLE K-2

GAS FLOW AND COAL FIRING RATE CALCULATIONS

Annubar reading = 42,000 scfm

Temperature at annubar = 278°F

Pressure at annubar = 25" H_2O

Corrected gas flow rate = 42,000 scfm x $\frac{370 + 460^{\circ}R}{278 + 460^{\circ}F}$ x

$$\frac{14.7 + 25\ (14.7/407)\text{psia}}{14.8\ \text{psia}} = 49{,}798\ \text{scfm}$$

(The Annubar was supplied and calibrated for a gas temperature of 370°F and 14.8 psia)

Between 10:45 AM and 5:55 PM, total coal burned = 32,736 lbs.
= 4568 lbs/hr.

Sulfur content of coal = 2.62%, heating value = 11,400 Btu/lb as received. (These figures are based on coal analysis)

Assume 93% of sulfur in the coal is burned to SO_2 and emitted from boiler. (This assumption is based on overall heat plant efficiency data collected in Oct. 1974)

SO_2 rate = (4568 lbs/hr)(0.0262 lb.S/lb.coal) (0.93) (64#SO_2/32#S) = 222.61 lbs/hr.

Heat production = (11,400 Btu/lb) (4568 lb/hr) = 52.08×10^6 Btu/hr

Moisture in gas = 5.0%

Corrected (dry) gas flow = (49,798) (0.95) = 47,308 scfm

TABLE K-3 SO$_2$ EMISSION RATE CALCULATIONS

Test 1

Volume collected = 8.0769 + 7.7594 = 15.8363 ft^3

Barium chloride titration: 0.2027gmSO$_4^{=}$/l

$$SO_2 \text{ rate} = \frac{47{,}308\text{scfm} \times 0.7027\text{gm/l}}{15.8363\text{scf}} \times \frac{64\text{gm } SO_2/\text{gm mole}}{96 \text{ gm } SO_4^{=}/\text{gm mole}} \times$$

$$\frac{60 \text{ min/hr.}}{454\text{gm/lb.}} = 53.35\#/\text{hr.}$$

$$SO_2 \text{ rate per million Btu} = \frac{53.35\#/\text{hr.}}{52.08\text{MM Btu/hr.}} = 1.0243\#/\text{MMBtu}$$

Test 2

Volume collected = 7.7531 + 7.7218 = 15.4750 ft^3

Barium chloride titration: 0.1572 gm SO$_4^{=}$/l

$$SO_2 \text{ rate} = \frac{47{,}308 \times 0.1572}{15.4750} \times \frac{64}{96} \times \frac{60}{454} = 42.34\#/\text{hr.} = 0.8130\#/\text{MMBtu}$$

Test 3

Volume collected = 7.7612 + 7.7618 = 15.5230 ft^3

Barium chloride titration: 0.1293 gm SO$_4^{=}$/l

$$SO_2 \text{ rate} = \frac{47{,}308 \times 0.1293}{15.4750} \times \frac{64}{96} \times \frac{60}{454} = 0.6667\#/\text{MMBtu}$$

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